DYNAMO: Budget and TRMM Product Intercomparisons

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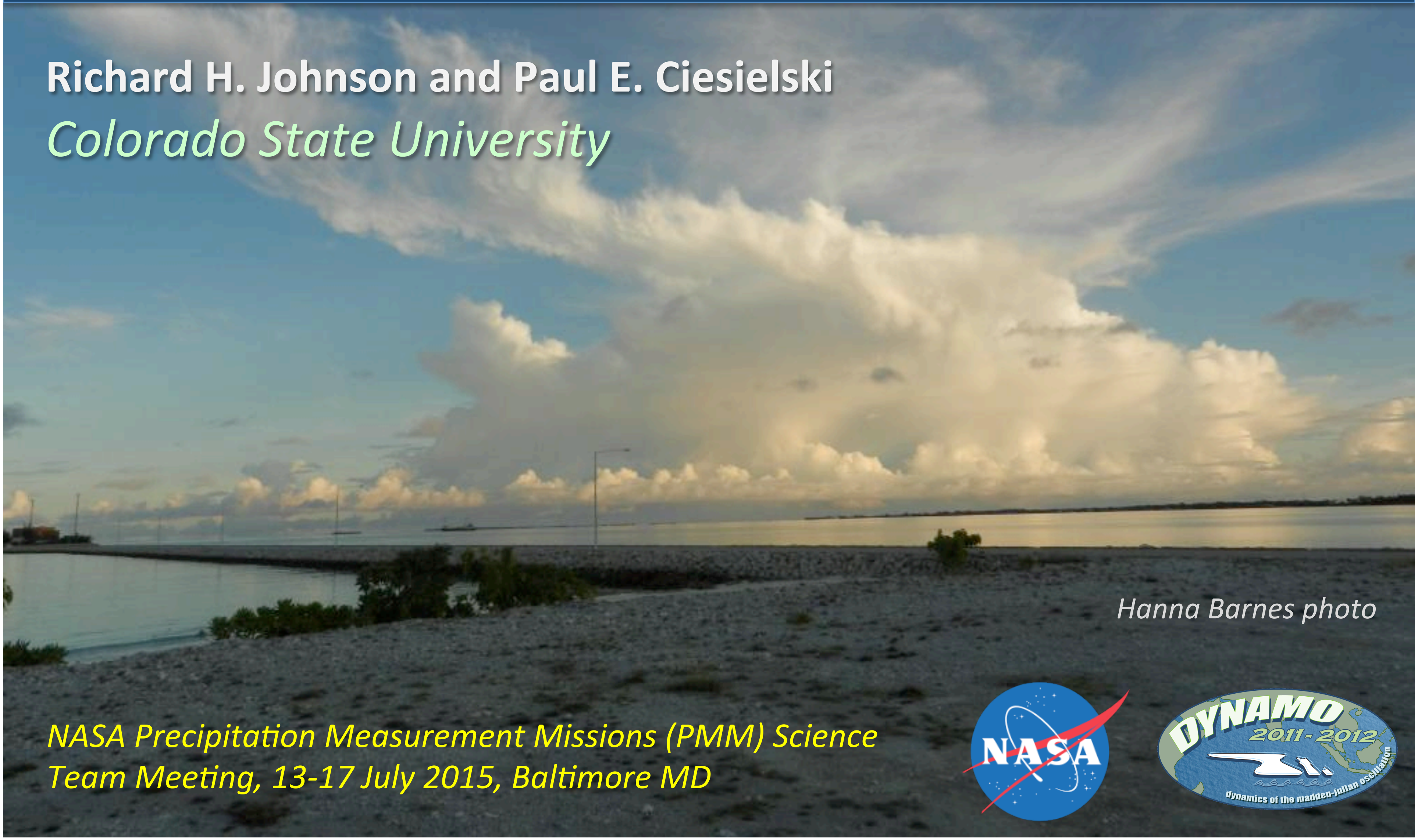
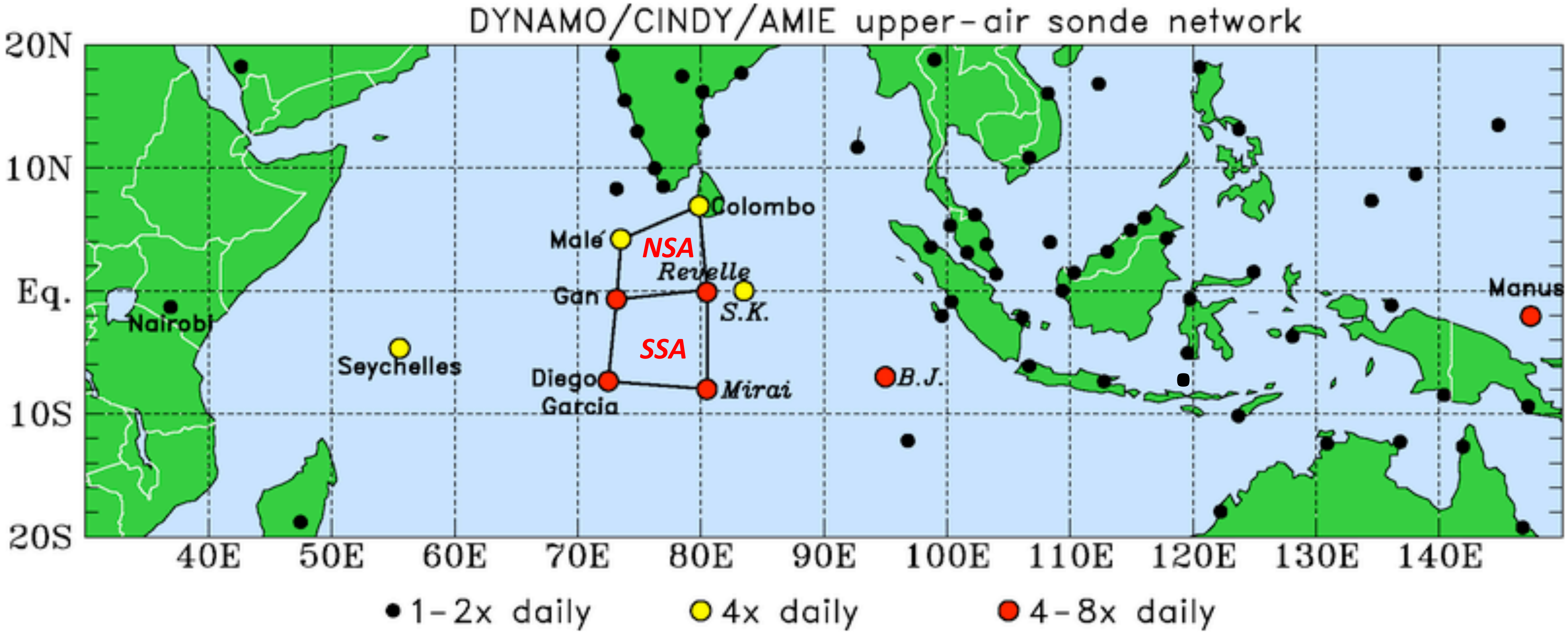


Hanna Barnes photo

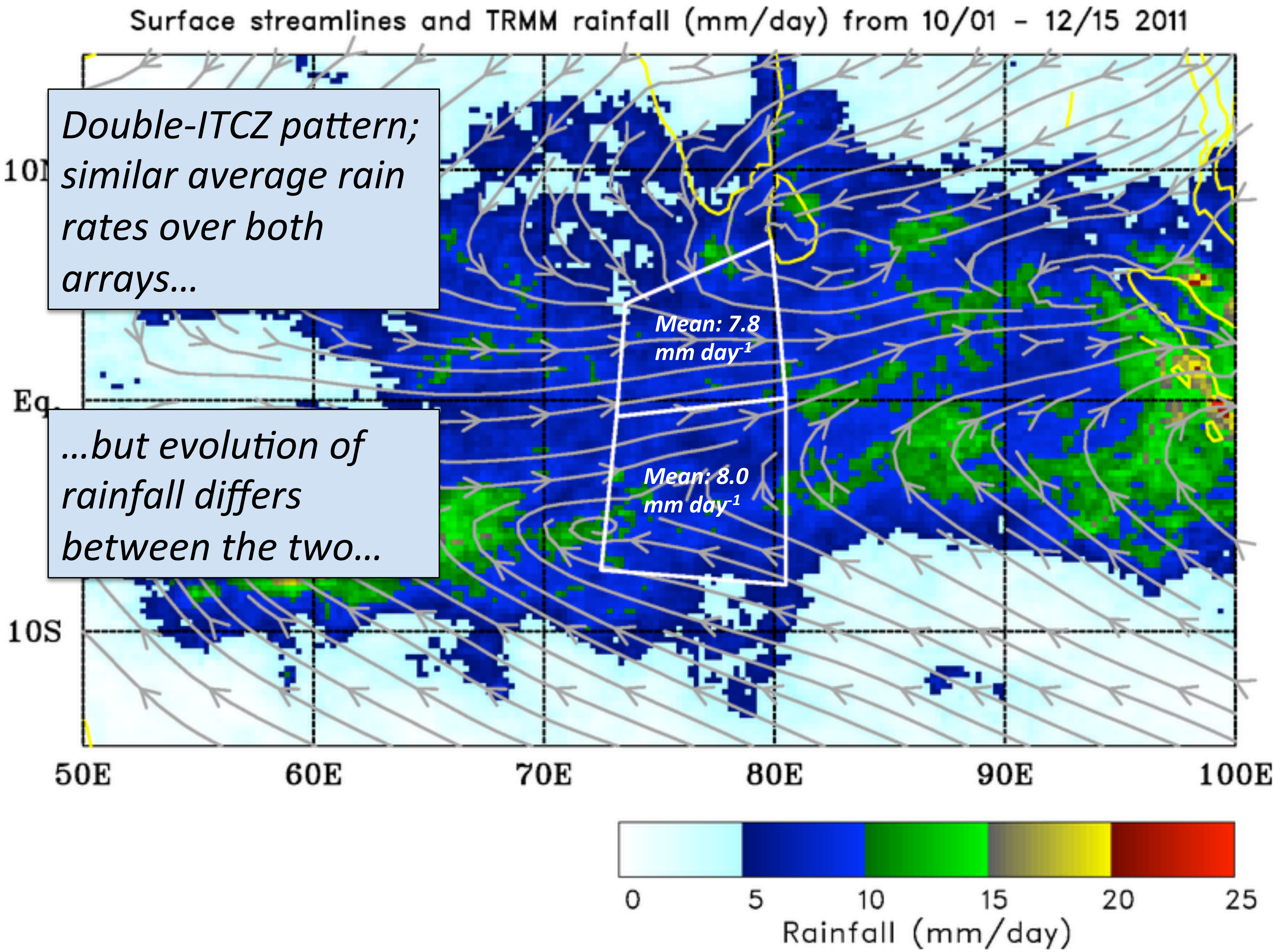
NASA Precipitation Measurement Missions (PMM) Science Team Meeting, 13-17 July 2015, Baltimore MD

DYNAMO/CINDY/AMIE Sounding Network

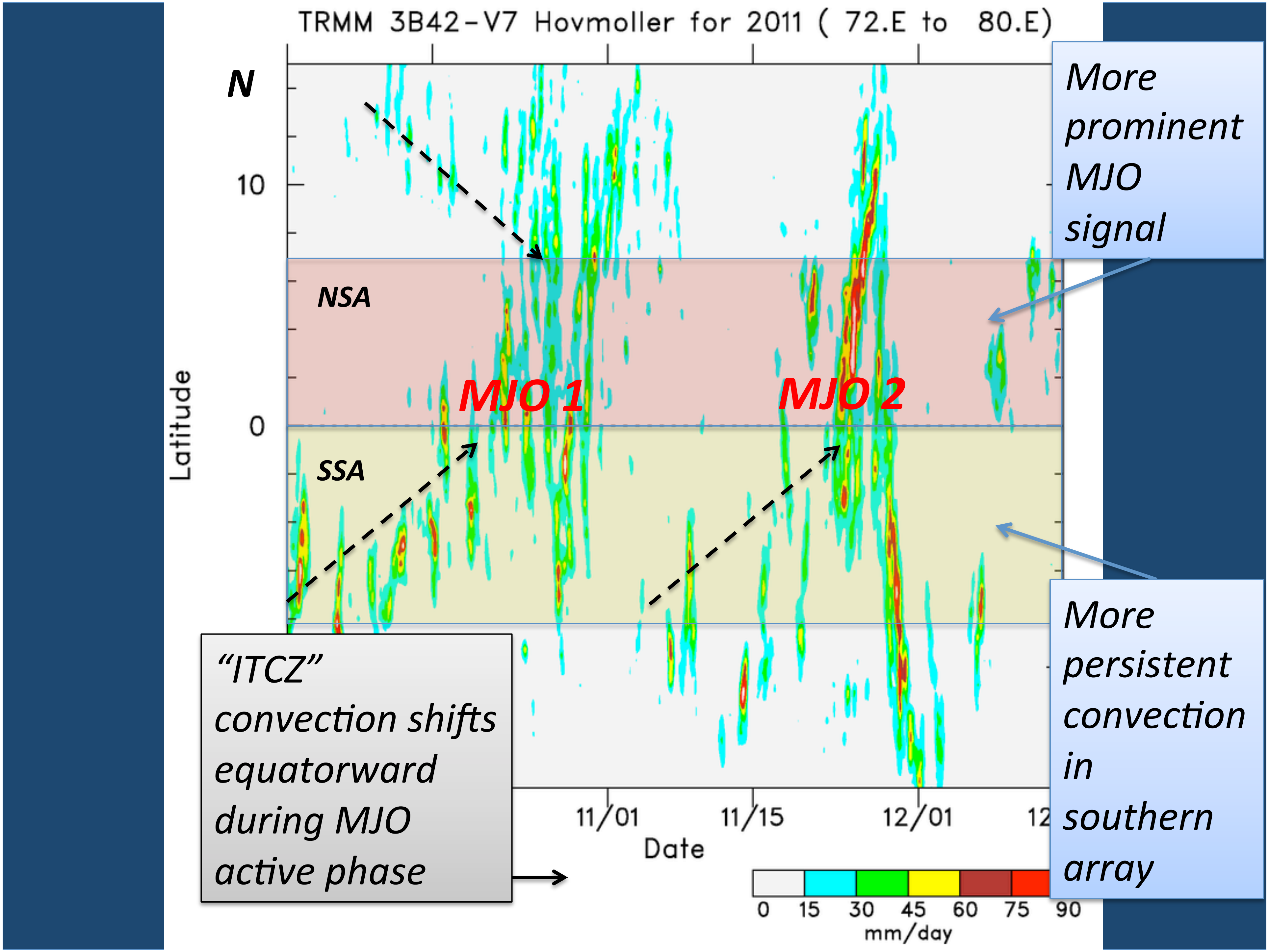


- ***Objective:*** *investigation of the initiation of the MJO over the Indian Ocean – the roles of large-scale advection, cloud populations, and air-sea interaction*

- *Qc'ed sounding data, along with satellite winds and COSMIC data, were objectively analyzed onto a 1° grid; large-scale budgets were computed, averaged over sounding arrays and compared to TRMM products.*

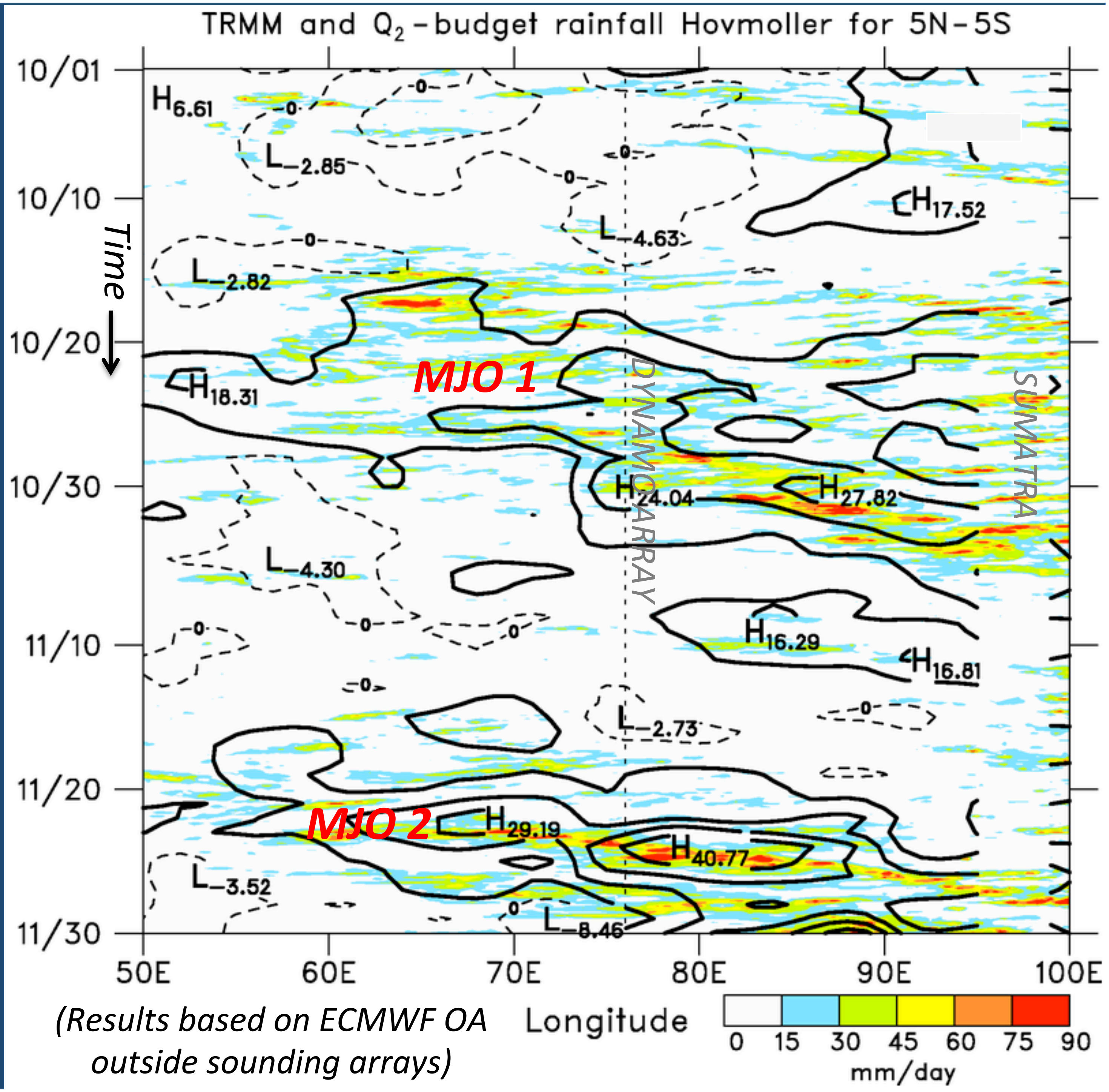


Surface streamlines and TRMM rainfall (mm/day) from 10/01 - 12/15 2011
Double-ITCZ pattern; similar average rain rates over both arrays…
…but evolution of rainfall differs between the two…
Mean: 7.8 mm day-1
Mean: 8.0 mm day-1
10N
Eq.
10S
50E
60E
70E
80E
90E
100E
0
5
10
15
20
25
Rainfall (mm/day)



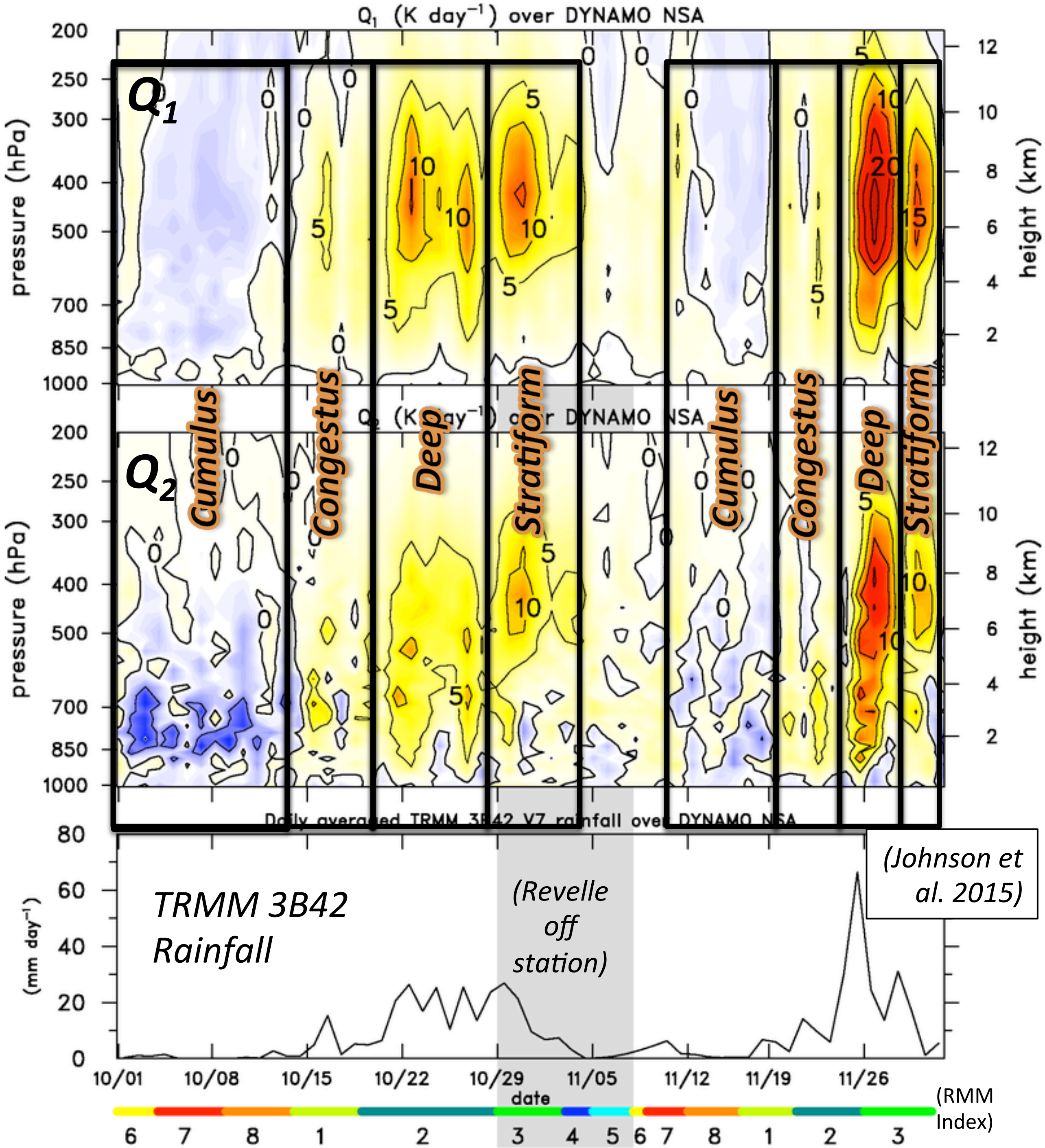
TRMM 3B42-V7 Hovmoller for 2011 (72.E to 80.E)
N
10
0
Latitude
NSA
SSA
MJO 1
MJO 2
11/01
11/15
12/01
12
Date
0
15
30
45
60
75
90
mm/day
More prominent MJO signal
More persistent convection in southern array
"ITCZ" convection shifts equatorward during MJO active phase

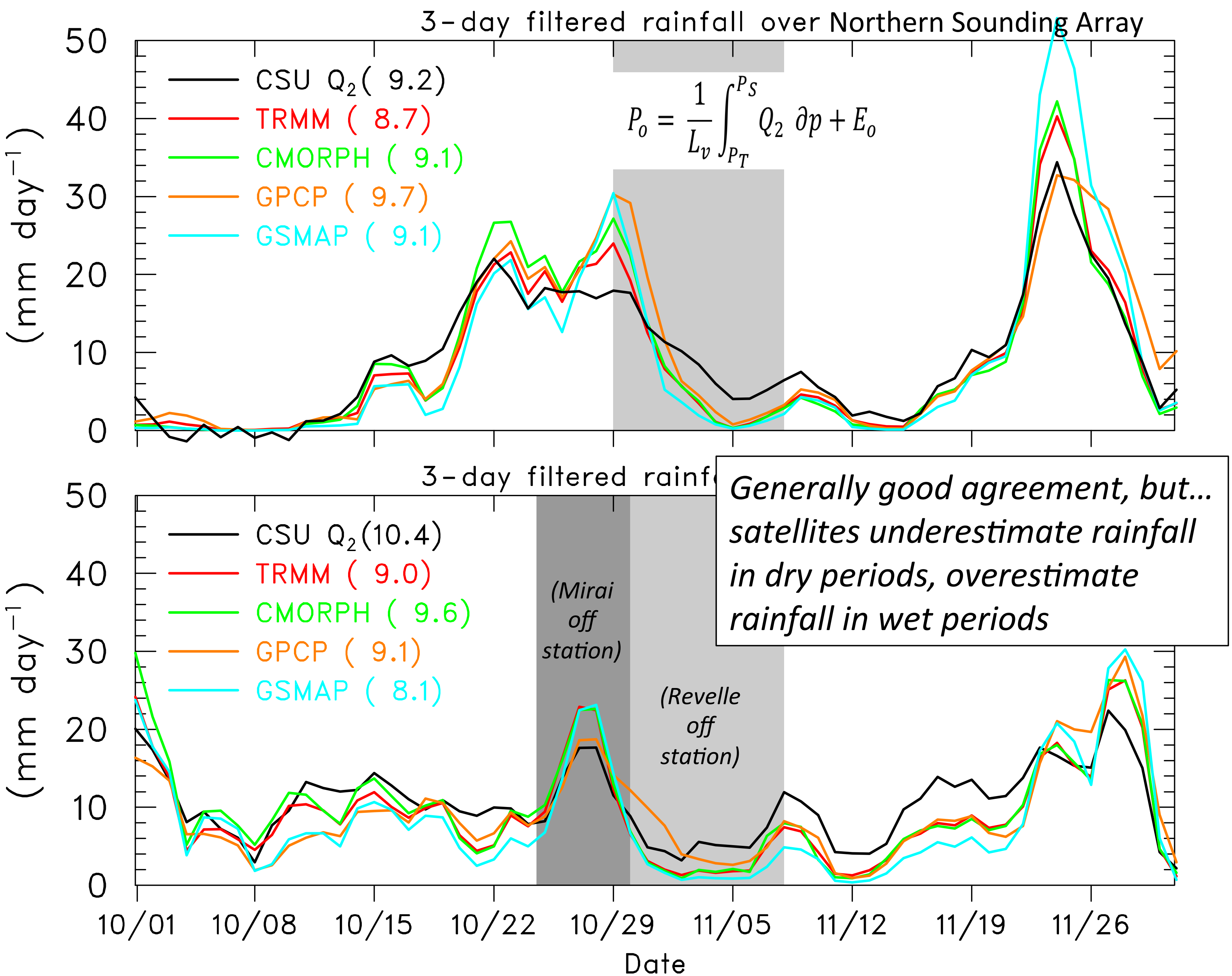
- Two prominent MJO events: October and November
- MJOs consist of westward- and eastward-moving disturbances
- Q_2 budget captures precipitation envelopes



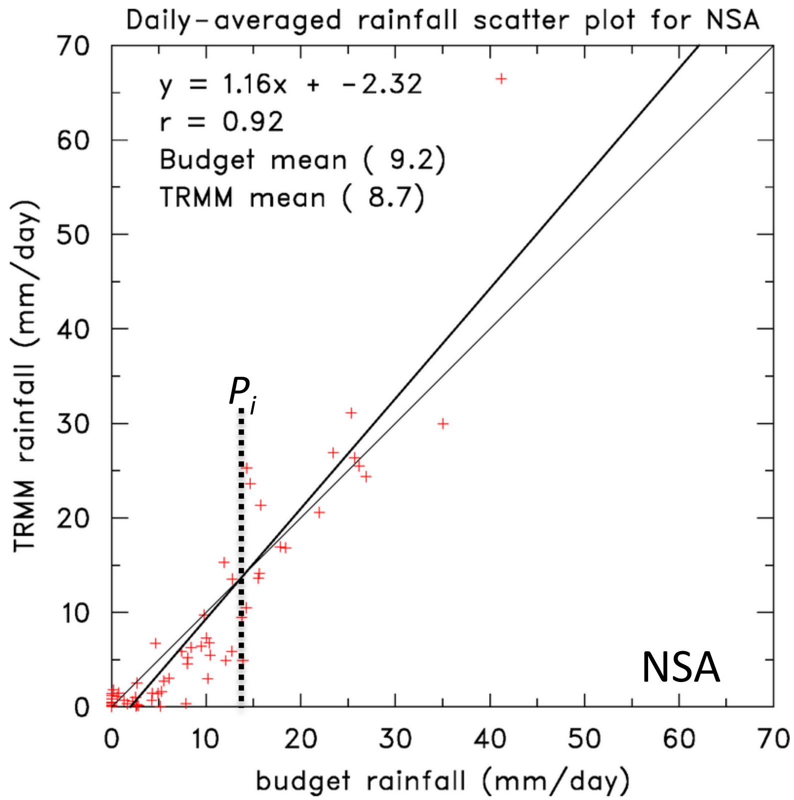
(Results based on ECMWF OA outside sounding arrays)

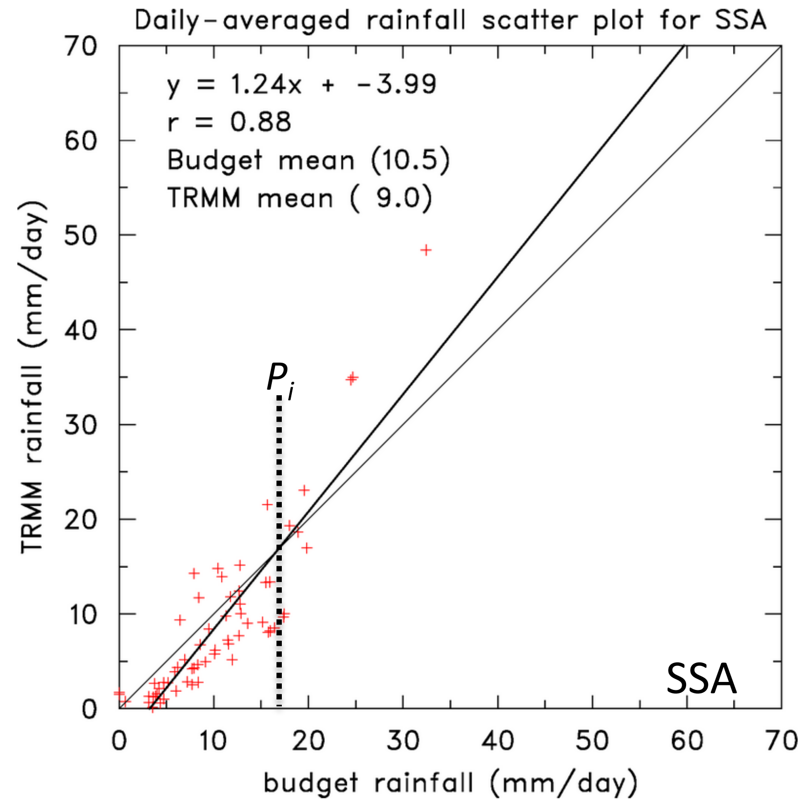
- *Preliminary inferences regarding dominant cloud populations:*
    - *Cumulus*
    - *Congestus*
    - *Deep convection*
    - *Stratiform*
- *Similar evolution for both MJOs, but shorter periods for each stage for MJO2*




3-day filtered rainfall over Northern Sounding Array
CSU Q_2(9.2)
TRMM (8.7)
CMORPH (9.1)
GPCP (9.7)
GSMAP (9.1)
$P_0 = \frac{1}{L_v}\int_{P_T}^{P_S} Q_2 \, \partial p + E_0$
3-day filtered rainf
CSU Q_2(10.4)
TRMM (9.0)
CMORPH (9.6)
GPCP (9.1)
GSMAP (8.1)
(Mirai off station)
(Revelle off station)
Generally good agreement, but… satellites underestimate rainfall in dry periods, overestimate rainfall in wet periods
(mm day^{-1})
Date
10/01
10/08
10/15
10/22
10/29
11/05
11/12
11/19
11/26

Scatter plots of Rainfall (TRMM 3B42 vs Budget-derived)

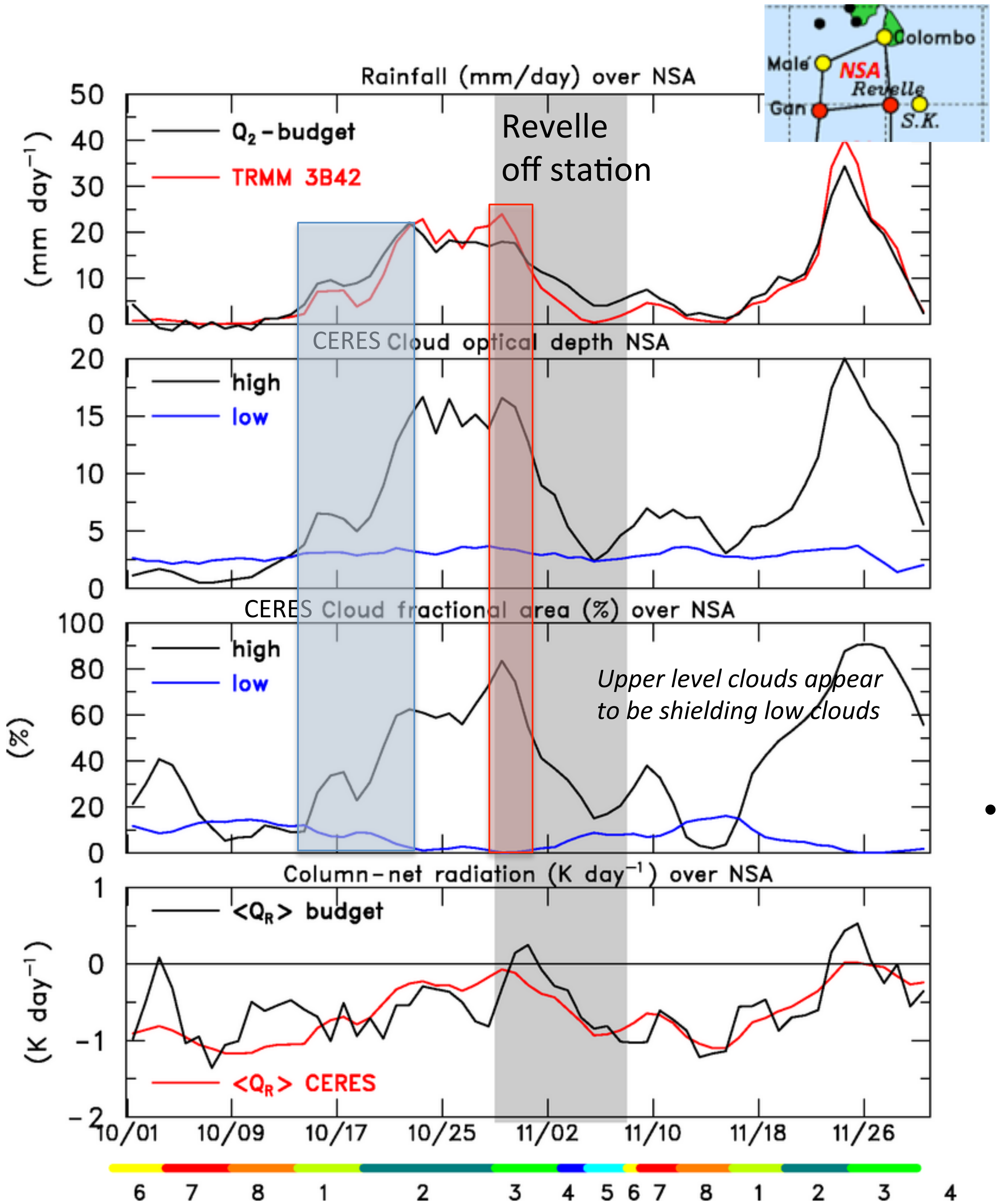




P_i @ 14.2 mm/day
Below P_i: TRMM – Budget = -2.1 mm
Above P_i: TRMM – Budget = 3.7 mm

P_i @ 16.6 mm/day
Below P_i: TRMM – Budget = -2.5 mm
Above P_i: TRMM – Budget = 5.5 mm

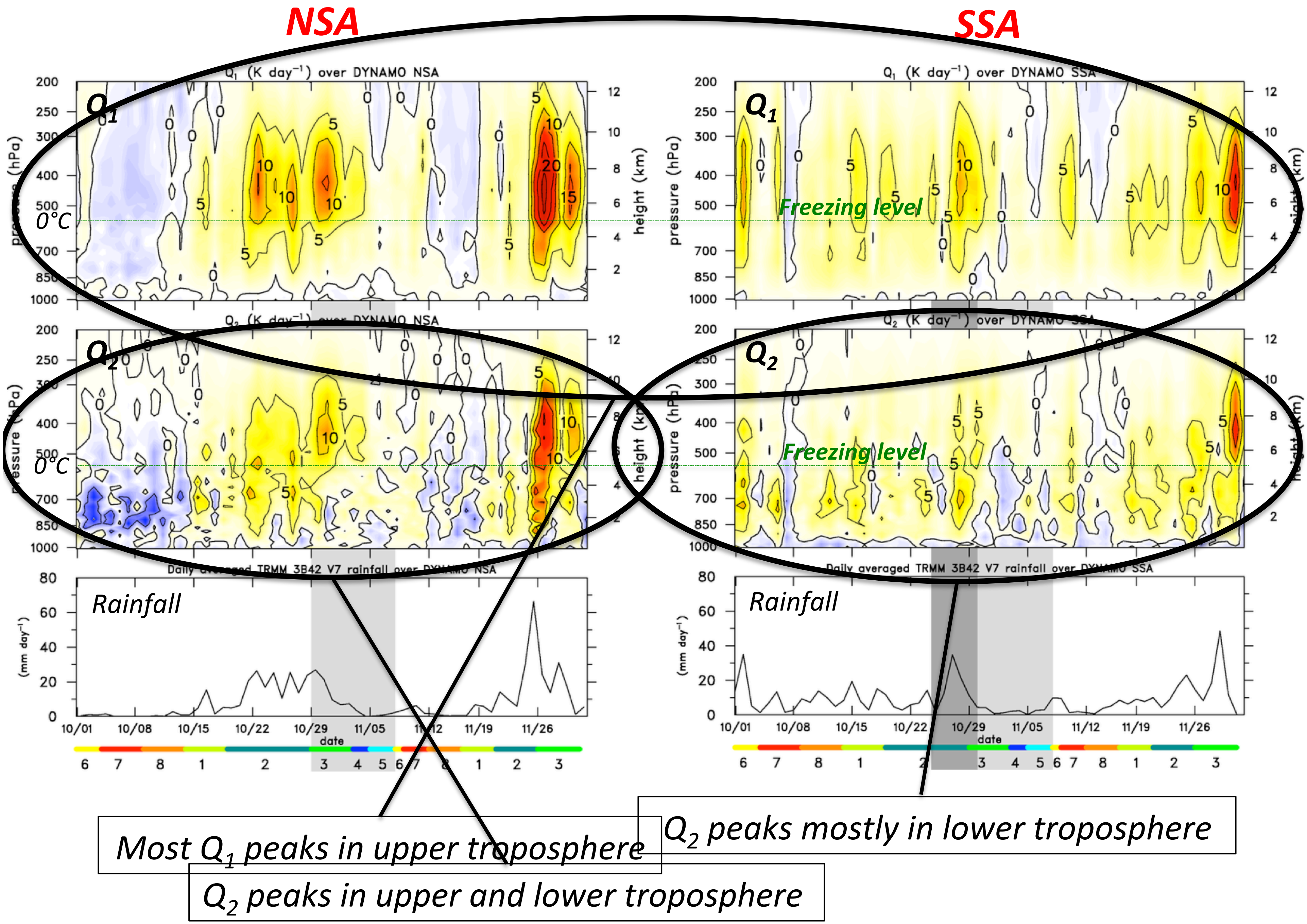
- This corroborates the finding of Xu and Rutledge (2014), based on radar data from *RV* Revelle, where they found that TRMM 3B42 rainfall product:
  - ***underestimates*** *rainfall during suppressed periods* (presumably due to insufficient sampling of shallow, warm-rain clouds)
  - ***overestimates*** *rainfall during convectively active periods* (likely due to abundance of high-level cloudiness).



- Rainfall differences increase over NSA when Revelle was off station
- Condensate storage in clouds may be contributing to rainfall differences.

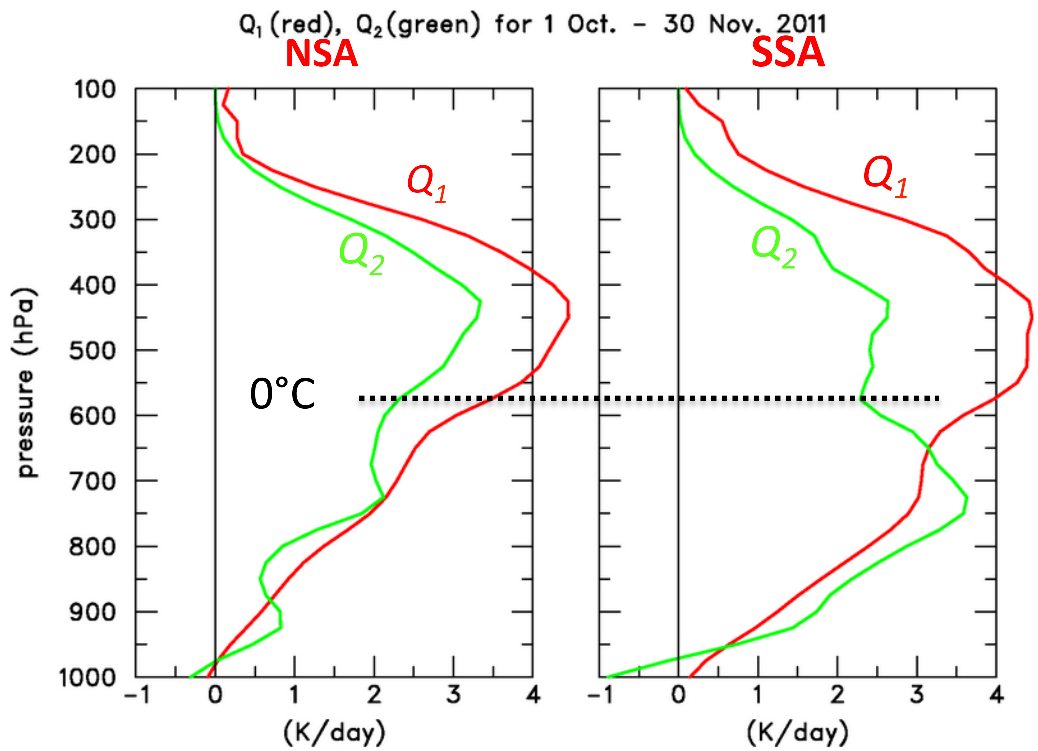
- When cloud field is increasing, budgets will tend to overestimate rainfall
- Conversely, when cloud field is decreasing, budgets tend to underestimate rainfall

- Strong correlation between $<Q_R>$ and upper-level cloudiness (i.e., $|<Q_R>|$ *decreases as high-cloudiness increases) confirms important role of high cloudiness in trapping longwave radiation.*



NSA
SSA
Q1 (K day-1) over DYNAMO NSA
Q1 (K day-1) over DYNAMO SSA
Q2 (K day-1) over DYNAMO NSA
Q2 (K day-1) over DYNAMO SSA
Daily averaged TRMM 3B42 V7 rainfall over DYNAMO NSA
Daily averaged TRMM 3B42 V7 rainfall over DYNAMO SSA
Q1
Q2
0°C
Freezing level
Rainfall
pressure (hPa)
height (km)
(mm day-1)
date
10/01 10/08 10/15 10/22 10/29 11/05 11/12 11/19 11/26
Most Q1 peaks in upper troposphere
Q2 peaks in upper and lower troposphere
Q2 peaks mostly in lower troposphere

2 month-mean vertical profiles

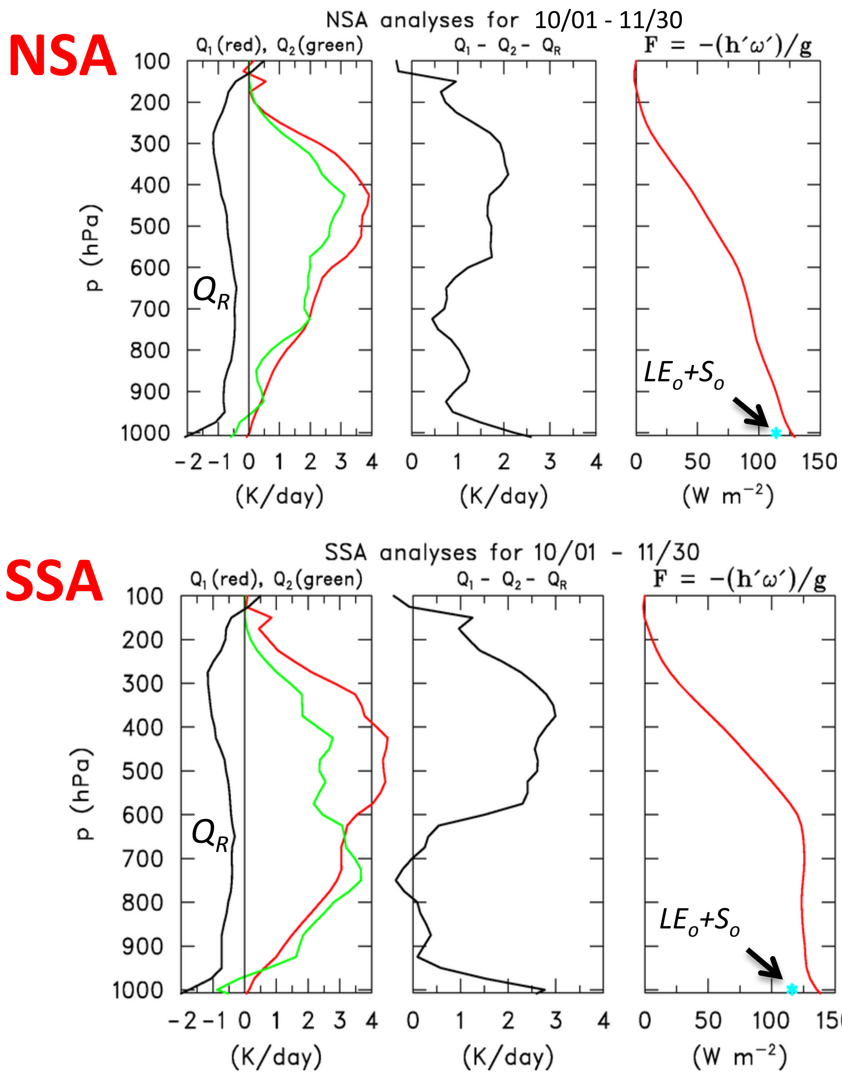


- Both arrays have peak heating level near 425 hPa; peak for SSA is somewhat broader.
- Q_2 peaks near 400 hPa for NSA; below 700 hPa for SSA

- Over the NSA, Q_1 and Q_2 peaks are coincident in the vertical; while over the SSA a large vertical separation is present in these peaks
- Suggest that vertical convective eddies are stronger over SSA

Profiles of vertical eddy flux of moist static energy

$$F(p) = -\frac{1}{g}\,(h'\omega') = \frac{1}{g}\int_{p_T}^{p}(Q_1 - Q_2 - Q_R)\partial p$$



- $Q_R(p)$ over arrays is estimated by adjusting Gan $Q_R(p)$ so that its vertical integral matches the CERES array-averaged $\langle Q_R \rangle$

- Upper-level eddy flux convergence is larger over SSA resulting in stronger and deeper convective eddy fluxes (*F*) over this region.
- Weaker *F* over NSA implies that stratiform rainfall fraction (SF) may be more prominent over NSA.
- During this period SF from TRMM PR 2A25 is 55% over NSA and 50% over SSA for this period (*M. Katsumata*).

Validation of TRMM LH products for DYNAMO Oct-Nov. 2011 period

CSH (Convective-Stratiform Heating) *:*

- *Tao et al. (1993, 2000, 2001, 2006, 2010, 2015)*
- *Developers: Tao and Lang*
- 3H31v7
- **Monthly**, 0.5°, 19 vertical levels (0.5, 1, 2, … 18km)
- Q_1, *LH*, Q_R, Q_2

SLH (Spectral Latent Heating)

- *Shige et al. (2004, 2007, 2008, 2009)*
- *Developers: Shige and Takayabu*
- 3H25v7
- **Monthly**, 0.5°, 19 vertical levels
- $Q_1 - Q_R$, *LH*, Q_2

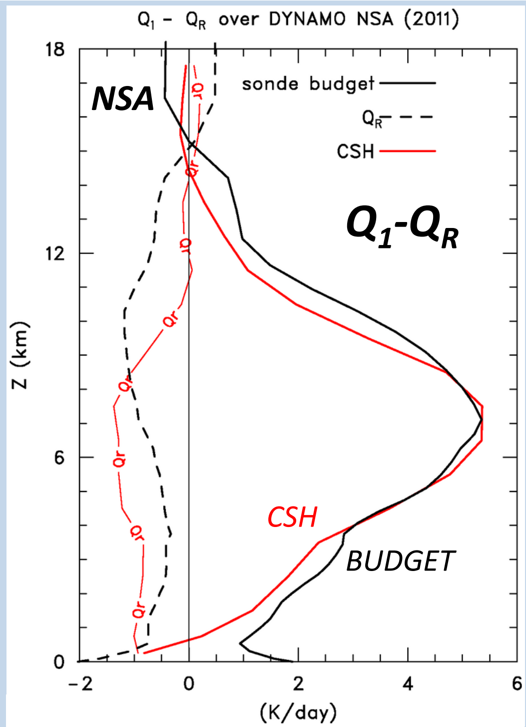
$Q_1 - Q_R$ = *LH + vertical eddy heat divergence*

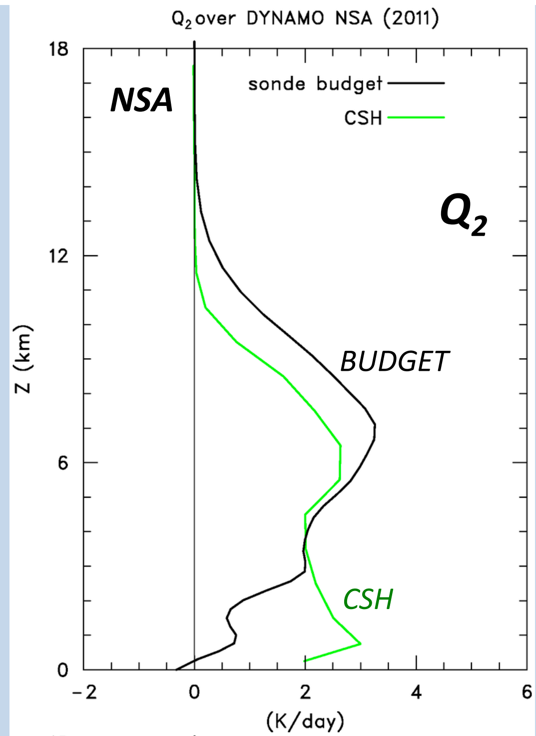
$Q_2 = Q_{c\text{-}e}$ + *vertical eddy moisture divergence*

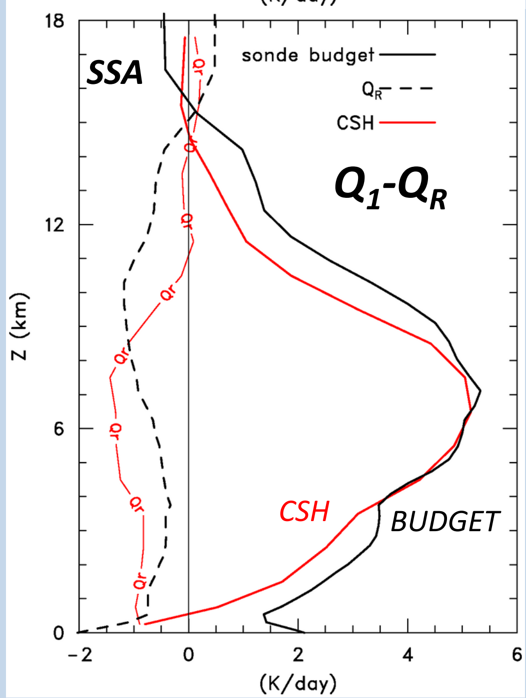
DYNAMO NSA/SSA Profiles:
Budget vs. CSH
Oct.-Nov. 2011

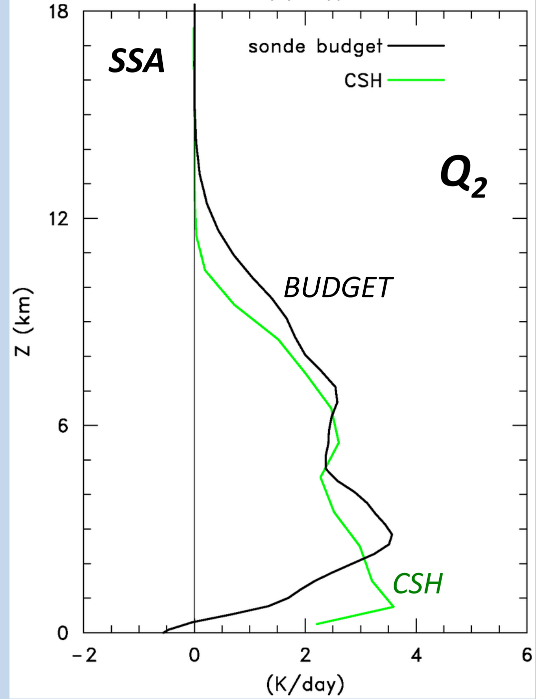
- *$Q_1 - Q_R$ budget profiles show good agreement with CSH*
- *Q_R differences account for some of the discrepancy in Q_1 - Q_R*
- *Budget Q_2 profiles differ between N and S arrays; CSH has similar Q_2 profile for both arrays*
- *Too much low-level drying in CSH*

(Q_R from Feng et al. 2014 based on Gan and CERES observations)



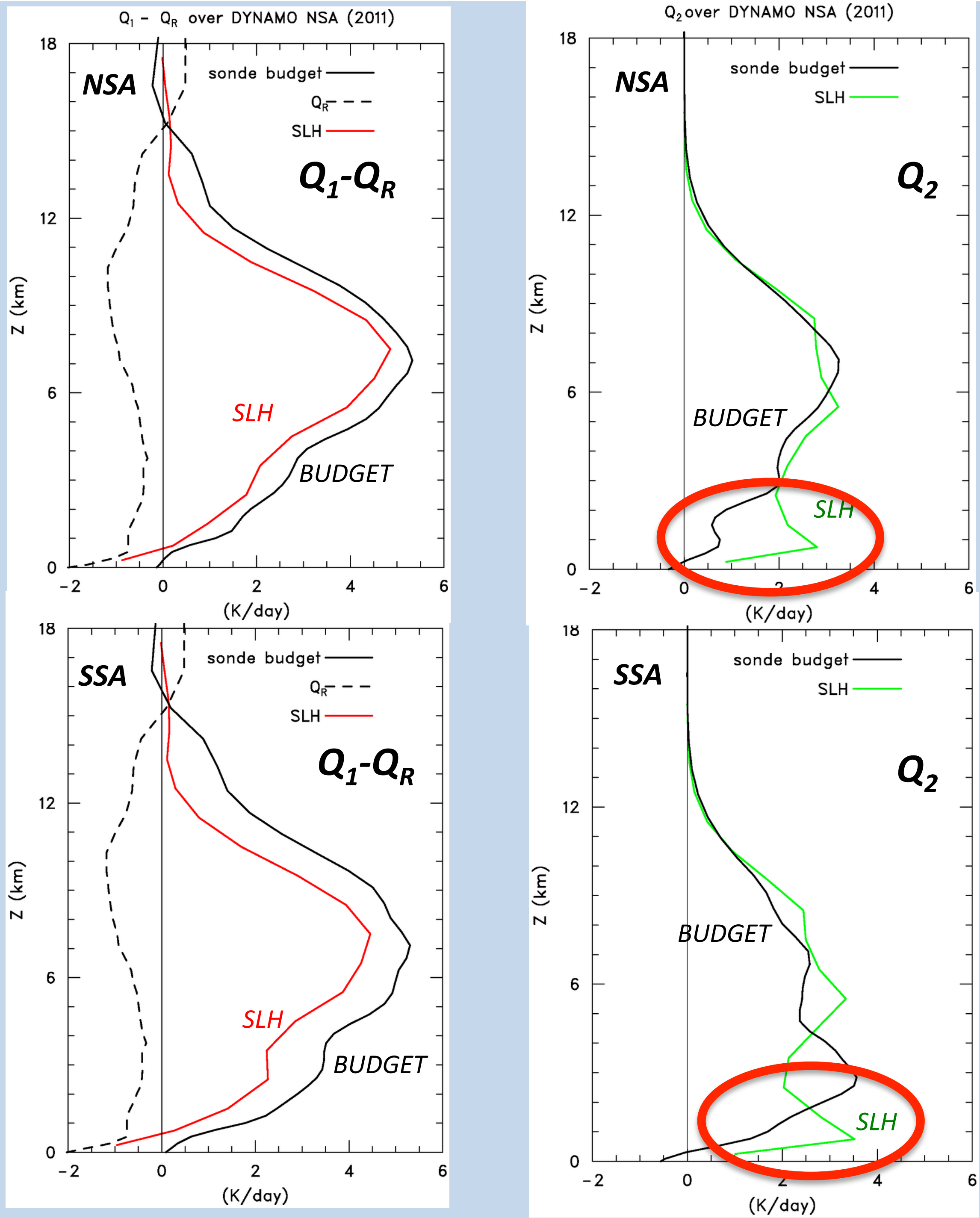




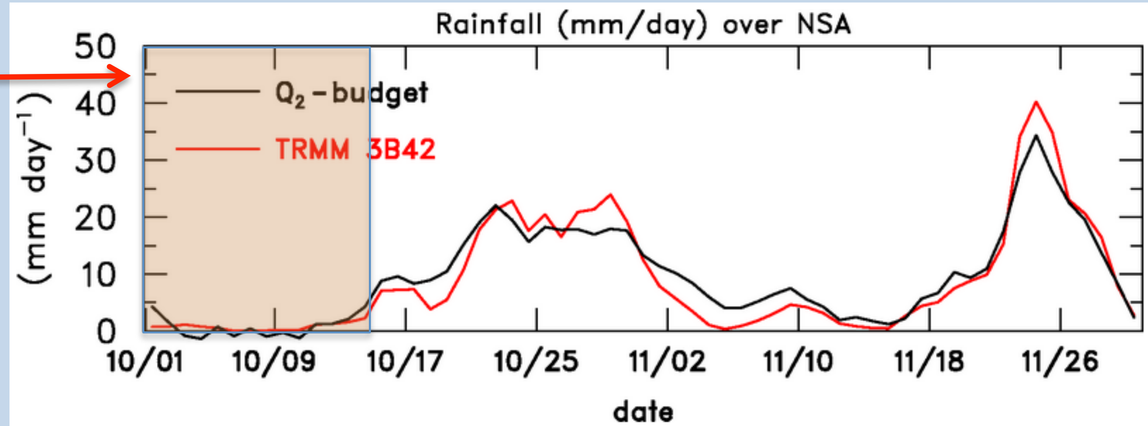


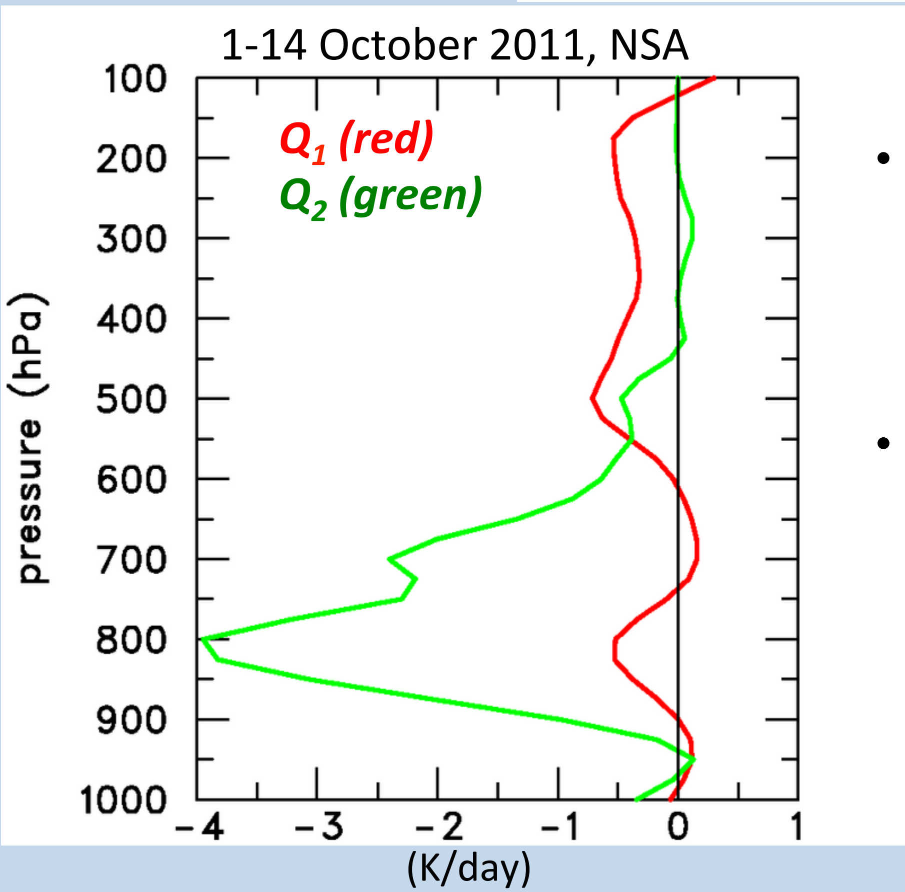
DYNAMO NSA/SSA Profiles:
Budget vs. SLH
Oct.-Nov. 2011

- *SLH $Q_1 - Q_R$ amplitude about 10% less than budgets*
- *SLH (as for CSH) has similar Q_2 profile for both arrays; implies similar cloud populations whereas budgets do not*
- *Similar to the CSH, SLH has excessive low-level drying*



- Little to no rainfall occurred during convectively suppressed period prior to October MJO active phase





- Strong low-level moistening and slight cooling during 1-14 October suggest the presence of shallow, non-precipitating convection during this period.

- Sensitivity of TRMM instruments prevent this type of convection from being detected which likely explains the excessive low-level drying in satellite Q_2 estimates.

Summary

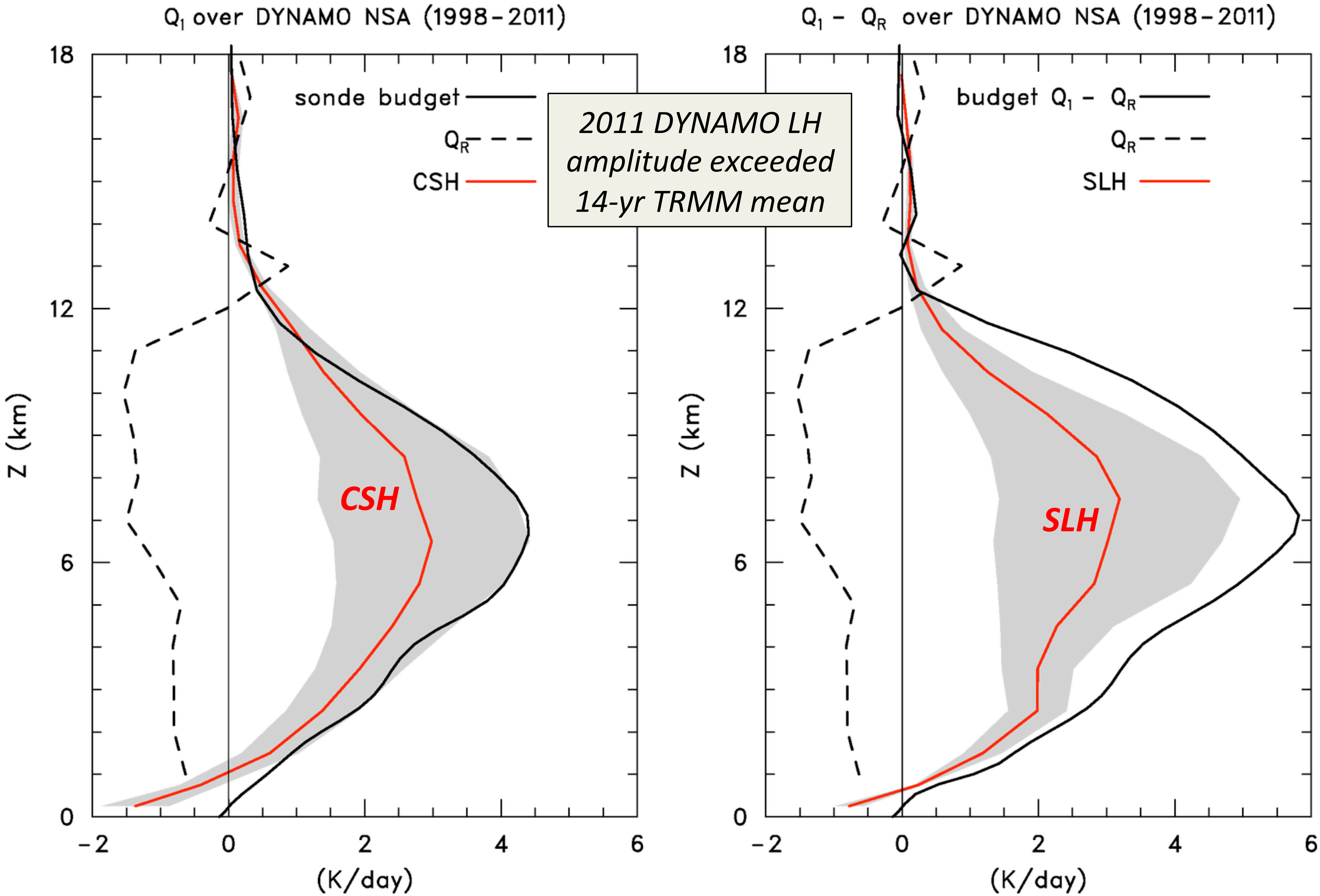
- Overall good agreement of budget-derived and satellite-based rainfall estimates during DYNAMO
- Differences in rainfall are due to sampling issues (soundings and satellites) and hydrometeor storage effects
- Convection over NSA was strongly modulated by MJO signal, while the SSA experienced more persistent, briefer episodes of rain related to ITCZ convection.
- Weaker vertical eddy fluxes over the NSA compared to SSA and TRMM 2A25 analyses suggest a higher stratiform rainfall fraction over the NSA (Lin et al. 2004).
- CSH and SLH heating profiles are in good agreement with budgets but satellite-based Q_2 profiles show more significant differences particularly at low-levels.

Dick Johnson launching a nighttime sounding in Malé during DYNAMO

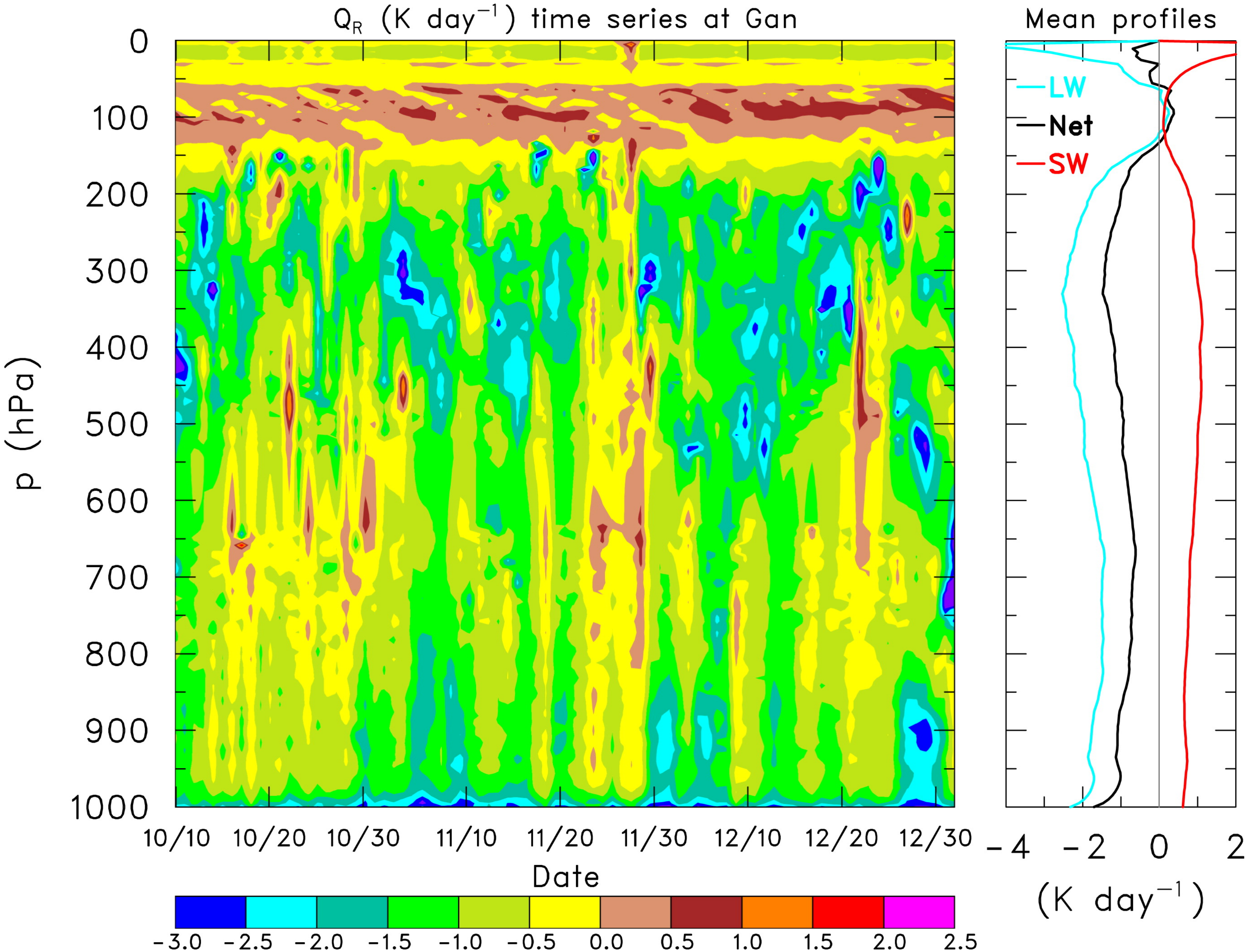
Supplemental material to follow

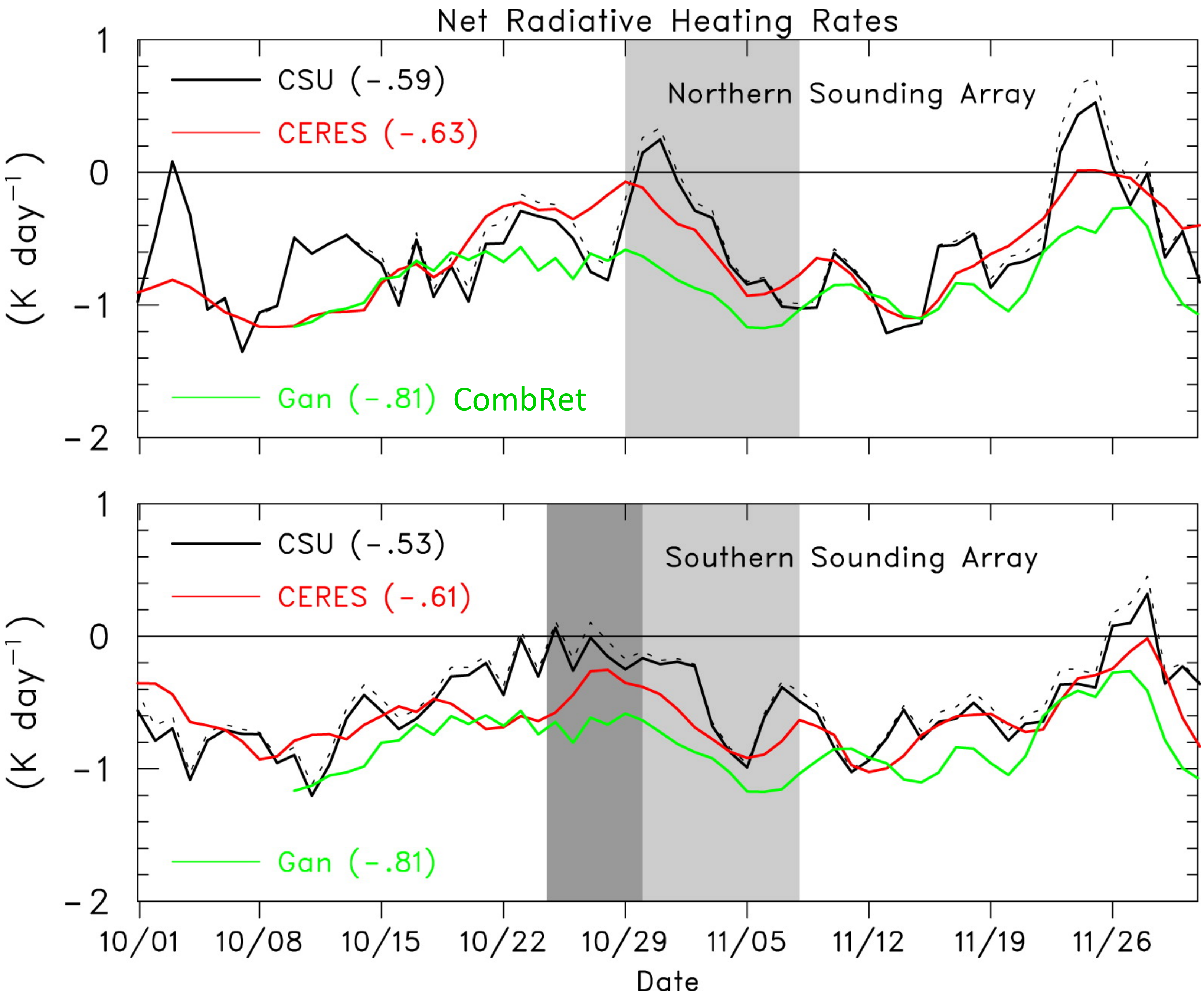
***CSH (3H25)**: Tao et al. (1993, 2000, 2001, 2006, 2010)*

***SLH (3H31)**: Shige et al. (2004, 2007, 2008, 2009)*



Radiative Heating Rates at Gan Island from CombRet



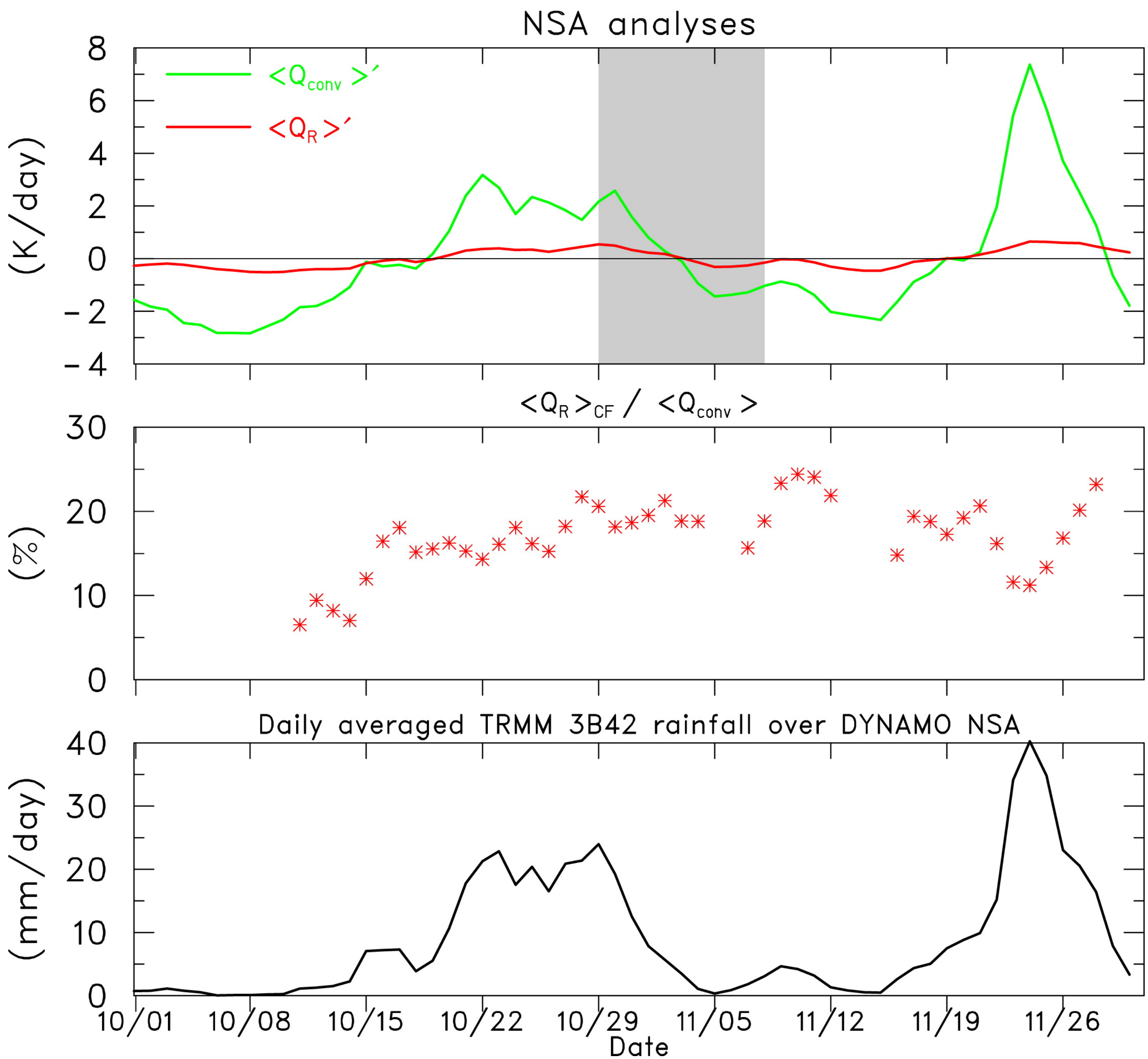


Net Radiative Heating Rates
CSU (-.59)
CERES (-.63)
Gan (-.81) CombRet
Northern Sounding Array
(K day^{-1})
1
0
-1
-2
CSU (-.53)
CERES (-.61)
Gan (-.81)
Southern Sounding Array
(K day^{-1})
1
0
-1
-2
10/01
10/08
10/15
10/22
10/29
11/05
11/12
11/19
11/26
Date

Latent and radiative heating anomalies

Ratio of cloud radiative forcing to convective heating

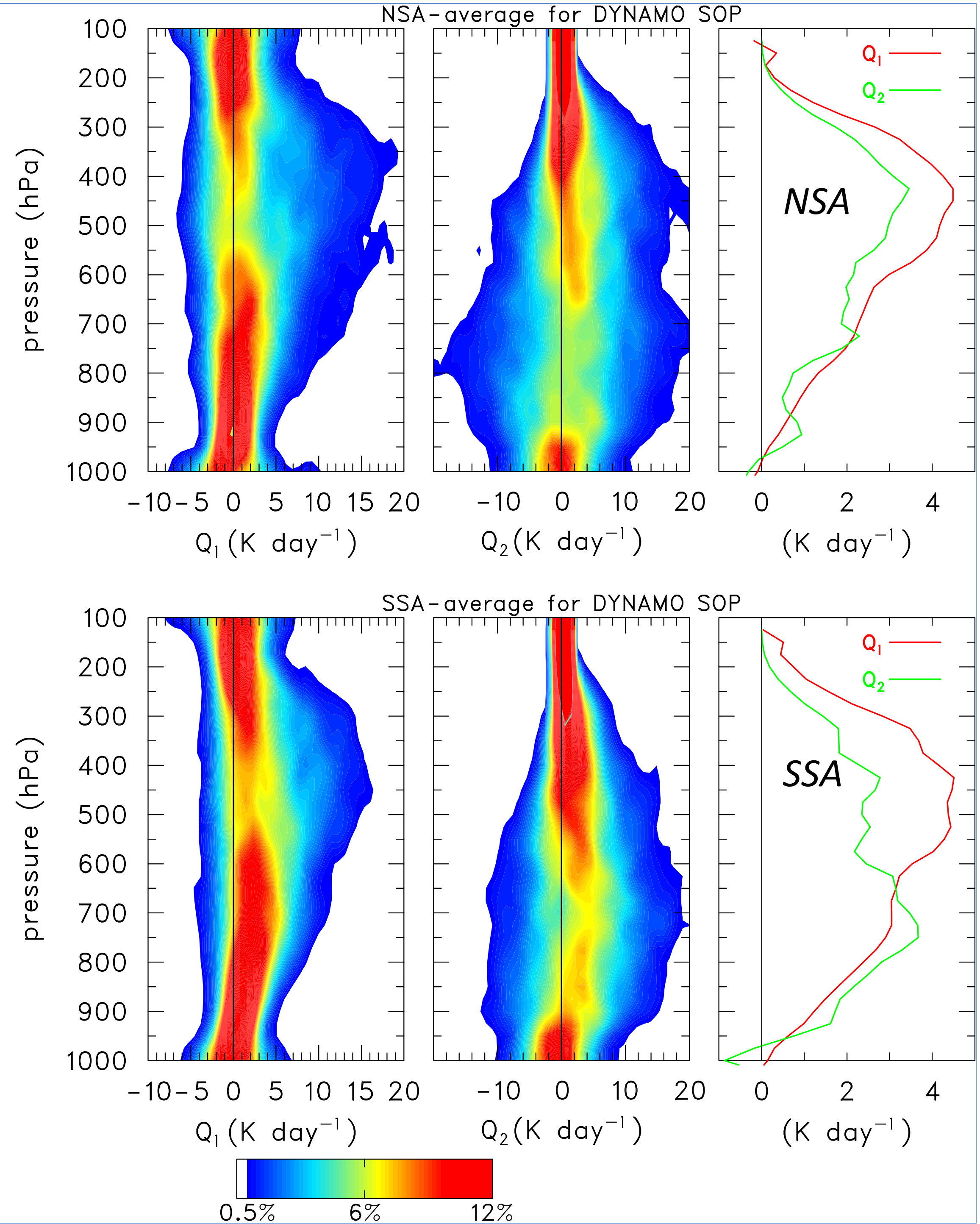
TRMM rainfall

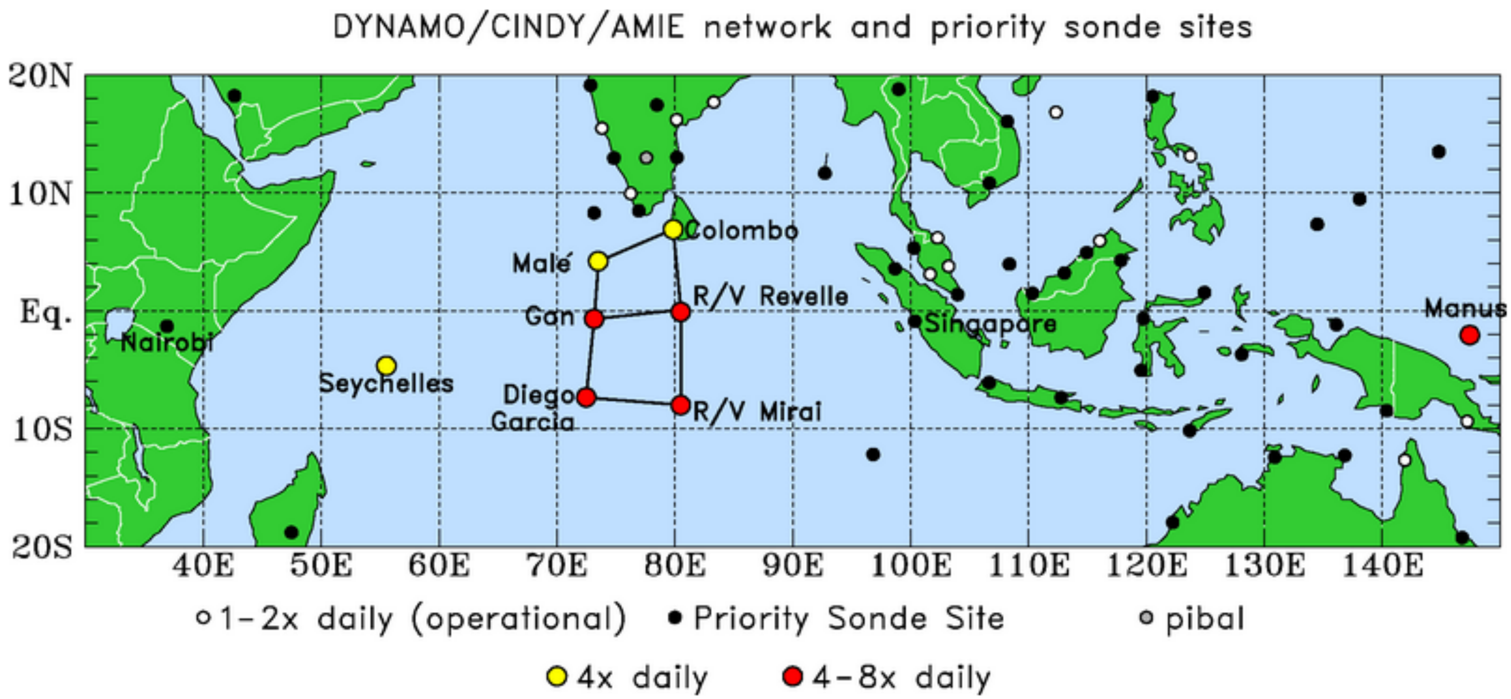


- *Mean profiles of Q_1 and Q_2 for NSA and SSA differ*

- *NSA more stratiform; SSA more convective – supported by TRMM measurements (SF = 55% for NSA, 50% for SSA)*

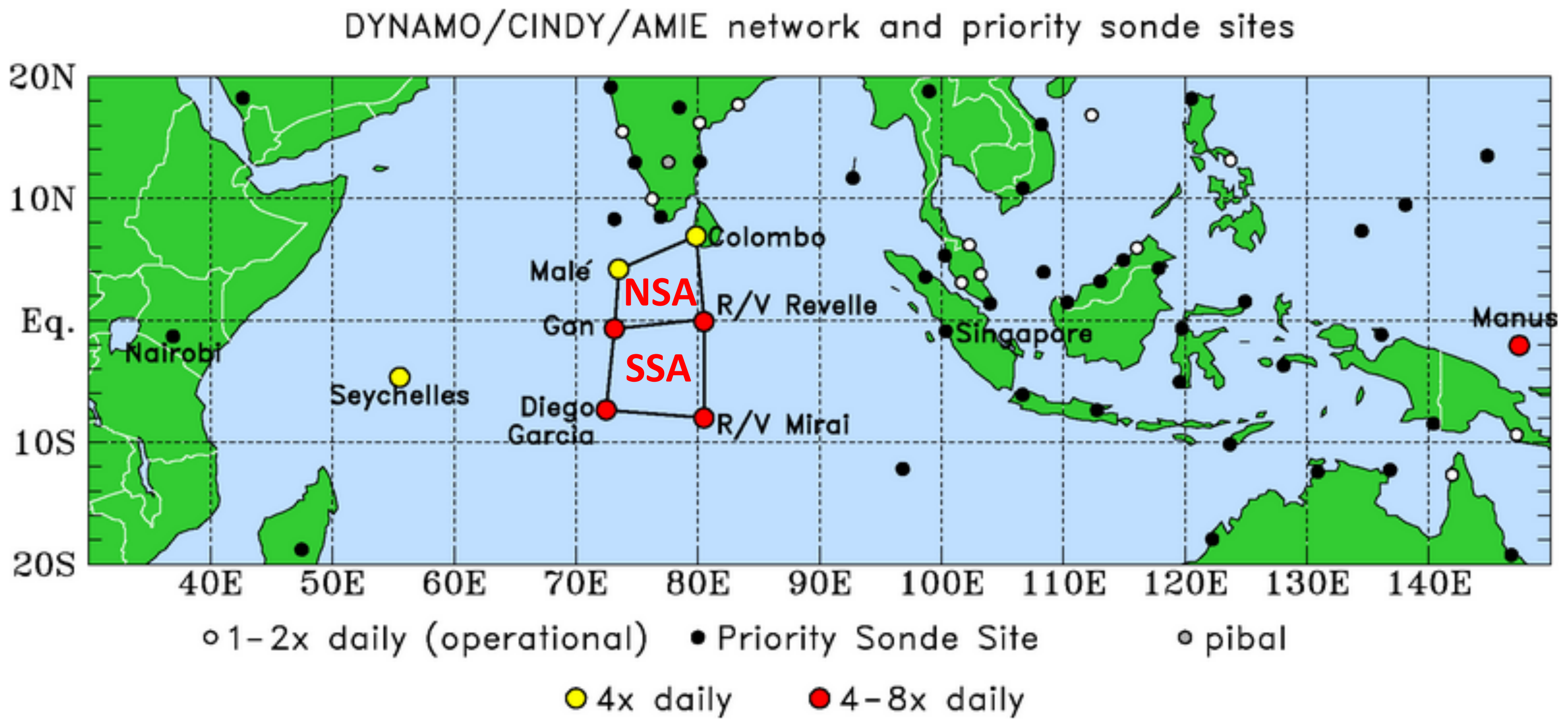
- *Consistent with findings by Lin et al. (2004) that MJO has greater stratiform rain fraction than tropical mean*





Input for Gridded Analyses

- Level 4 sounding data (uniform 5-hPa resolution) augmented with:
  - CIMSS cloud-drift satellite winds, ASCAT surface winds, and COSMIC thermodynamic profiles (T_d not used below 850 hPa)
- Enhancements to sounding data set:
  1. To better resolve the diurnal cycle, the 4/day soundings at Malé and Colombo were interpolated to a 3-h time resolution.
  2. An adjustment procedure was developed, making use of low-level ECMWF OA, to mitigate the Sri-Lanka island effects on Colombo soundings (Ciesielski et al. 2014)



Details for Objectively Analyzed Gridded Product

- Multiquadric interpolation to produce gridded analyses of basic fields
  - 3-hr, 1° horizontal res. (35-155°E, 20°S-20°N), 25-hPa vertical res. (sfc to 50 hPa)
  - Two versions of analyses were created: (V1) observations only, (V2) observations supplemented with ECMWF Operational Analyses (OA) in data sparse regions *outside* of core sonde network.
- Two versions produce similar results; except V2 provides a modest improvement in the budgets when ships are offsite
- Diagnostic fields computed with V2 analyses; results shown as array averages for the SOP (1 Oct. – 30 Nov. 2011) when sonde network was most complete.

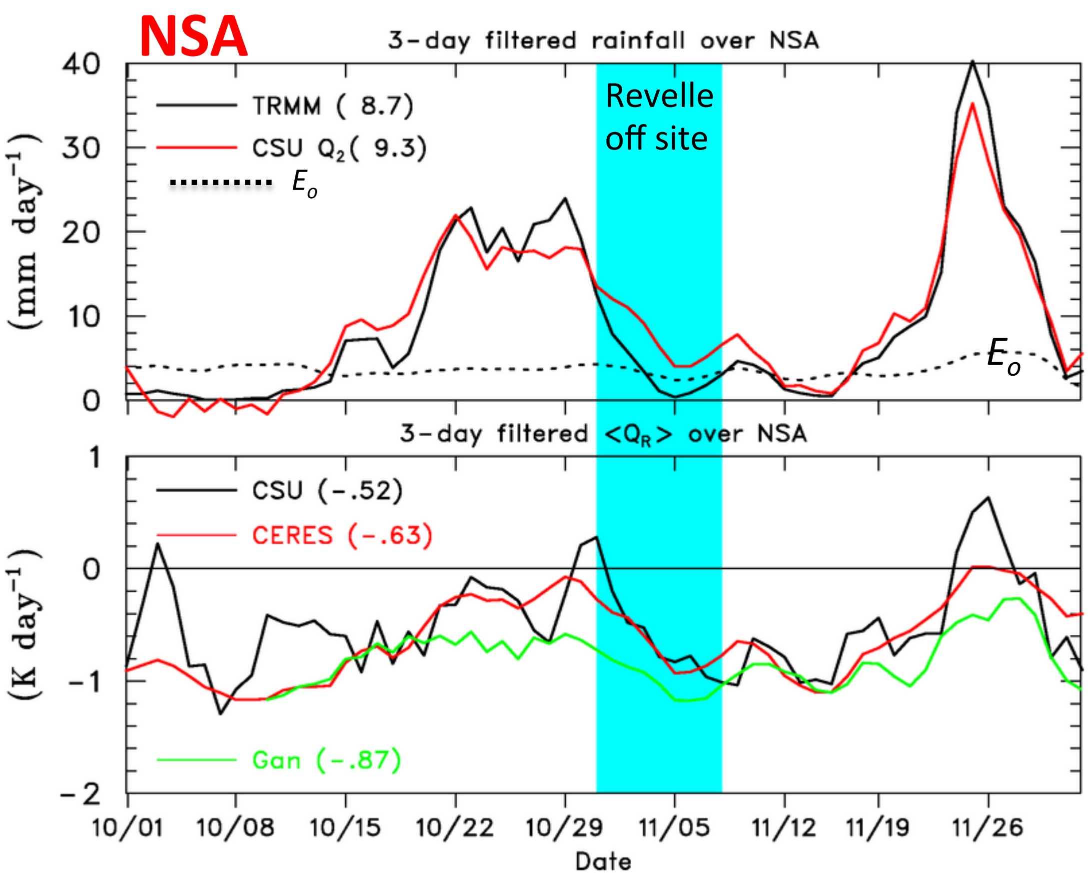
Evaluating budgets through integral constraints

$$P_o = \frac{1}{L_v}\int_{P_T}^{P_S} Q_2 \ \partial p + E_o$$

$$< Q_R > = \int_{P_T}^{P_S} (Q_1 - Q_2)\ \partial p - S_o - L_v E_o$$

E_o, S_o : WHOI OAFlux product (1°, daily)

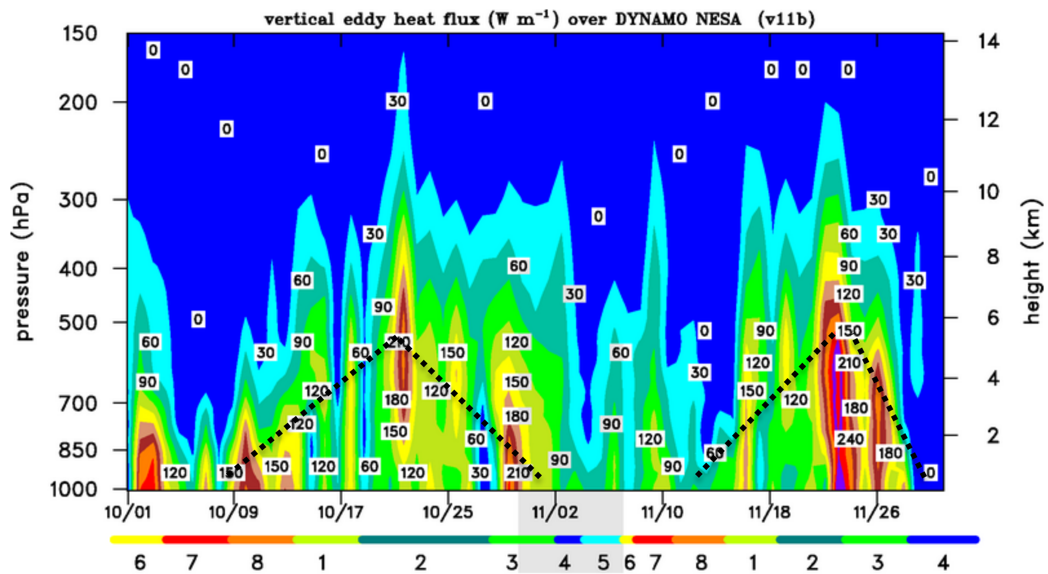
Validated against:
- TRMM 3B42V7 rainfall (3hr, 0.25°)
- CERES <Q_R> SYN1d product (3hr, 1°)
- Gan $Q_R(p)$, ARM CombRet (30s, 238 levels)



- Overall, excellent agreement between budget and independent estimates
- Largest P_o errors occur when Revelle is off site; budget uncertainty is large
- Other periods of P_o disagreement may be related to cloud-storage of water vapor.
- <Q_R> strongly modulated on MJO time scale, with much-reduced cooling during the active phases

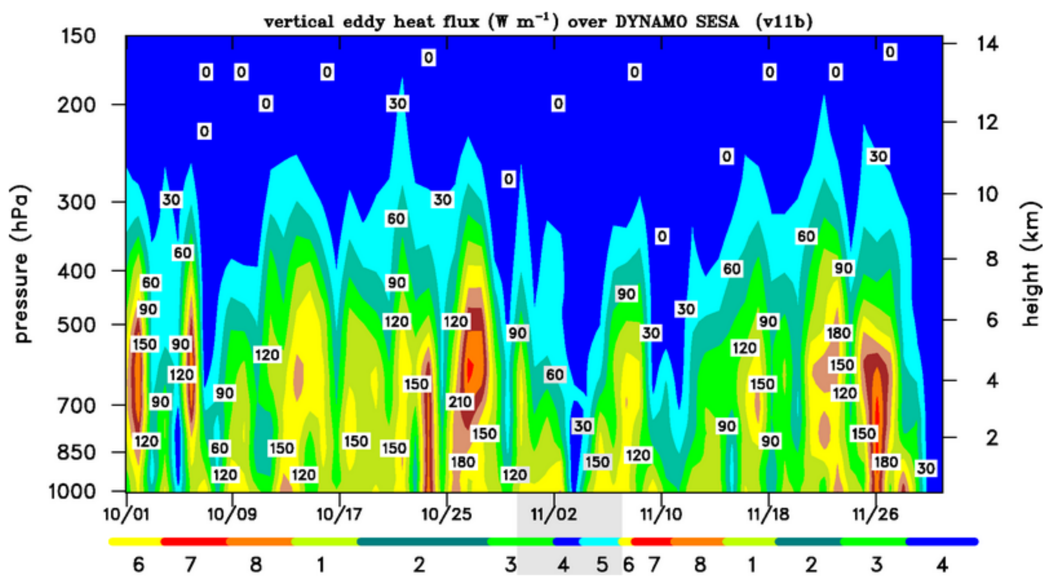
Time series of eddy flux of moist static energy *F(p)*

NSA



- Over NSA, eddy fluxes are strongly modulated on MJO time scale – being quite shallow during suppressed periods then deepening to peak at mid-level and gradually weakening near end of active phase.

SSA



- SSA is characterized with more persistent, deeper eddy fluxes.

Comparison of DYNAMO to TOGA COARE

Array	Size	# of sonde sites	Duration	Sounding frequency
DYN-NSA	$(707\ km)^2$	4	61 days	4-8/day
DYN-SSA	$(830\ km)^2$	4	61 days	8/day
TC IFA	$(474\ km)^2$	6	120 days	4/day

- NSA size is 50% > TC IFA
- SSA size is 75% > TC IFA

Experiment Mean Rainfall (mm day^{-1})

Array	Independent estimate	Q_2 Budget	*r*
DYNAMO NSA	8.7	9.3	0.96
DYNAMO SSA	9.0	10.4	0.91
TOGA COARE (IFA)	8.3 to 9.3	8.4	0.84

- High temporal correlations (*r*) indicate that budgets are accurately capturing the large-scale forcing signal.

Experiment mean $\langle Q_R \rangle$ (K day^{-1})

Array	Independent estimate	Budget	*r*
DYNAMO NSA	-0.63	-0.52	0.68
DYNAMO SSA	-0.62	-0.44	0.73
TOGA COARE (IFA)	-0.38 to -0.84	-0.55	0.43

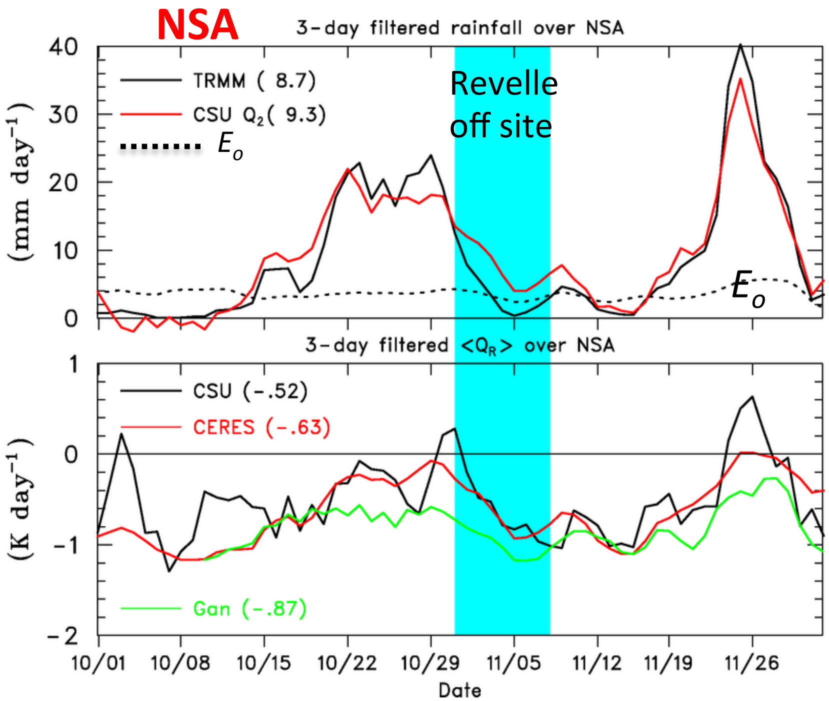
- Budget-estimated mean rainfall in DYNAMO is slightly higher than in TC and $\langle Q_R \rangle$ slightly less cooling

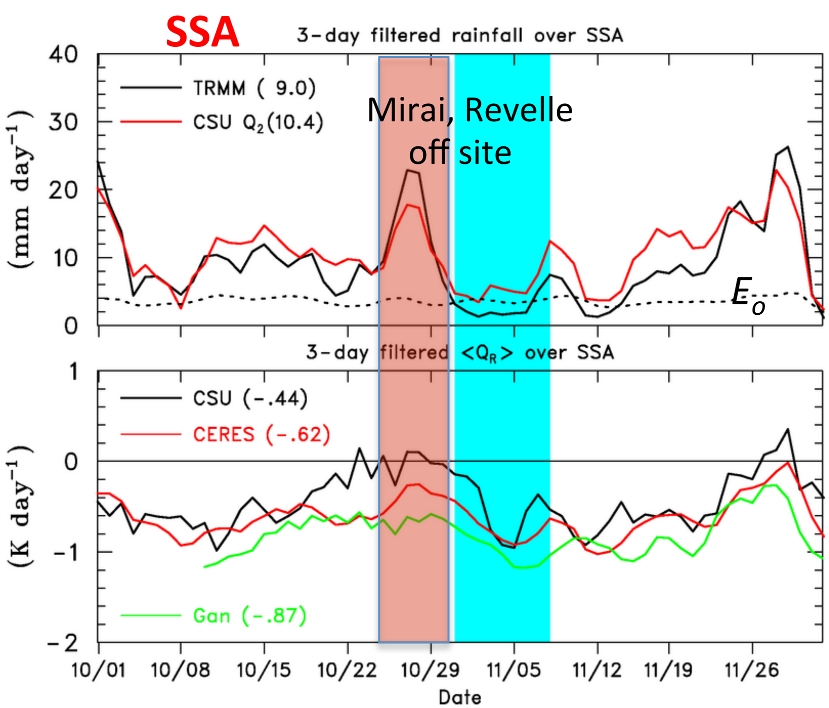
Supplemental material

Summary

- Budget analyses are based on a 3-h, 1°-gridded dataset which used high-quality upper-air soundings, satellite winds and COSMIC thermodynamic profiles as input.
- Supplementing these observation with model analyses results in a beneficial impact to the budgets when the ships are off site.
- Good agreement of budget-derived integral constraints (i.e. rainfall, $<Q_R>$, surface fluxes) with independent estimates lends confidence that **the budgets are accurately capturing the large-scale forcing signal.**
- Convection over NSA is strongly modulated by MJO signal, while the SSA experienced more persistent, briefer episodes of rain related to ITCZ convection.
- Weaker vertical eddy fluxes over the NSA compared to SSA suggest a higher stratiform rainfall fraction over the NSA (Lin et al. 2004).
- Plans are underway to create an ensemble forcing dataset such that the effects of random sampling errors on budgets can be investigated.

Thank you





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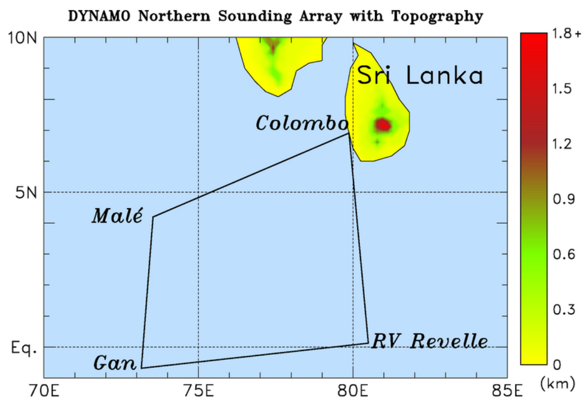
$$< Q_R > = \int_{P_T}^{P_S} (Q_1 - Q_2)\,\partial p - S_o - L_v E_o$$

E_0, S_0 : WHOI OAFlux product (1°, daily)

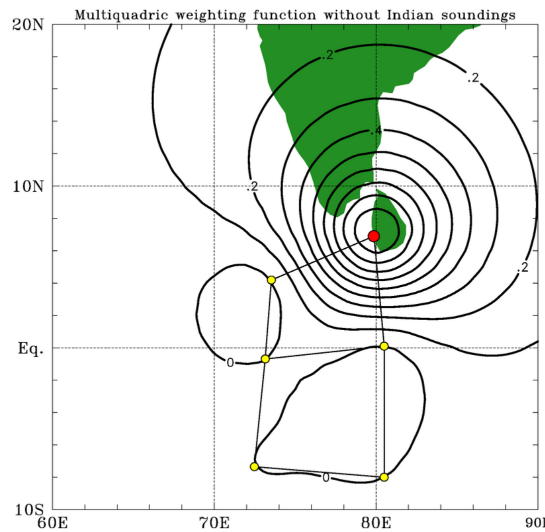
Validated against:
- TRMM 3B42V7 rainfall (3hr, 0.25°)
- CERES $\langle Q_R \rangle$ SYN1d product (3hr, 1°)
- Gan $Q_R(p)$, ARM CombRet (30s, 238 levels)

- Rainfall over SSA is more persistent and episodic than over NSA
- Correlations lower than over NSA
- Revelle off site 29 Oct. to 09 Nov.
- Mirai off site 24 Oct. to 30 Oct.

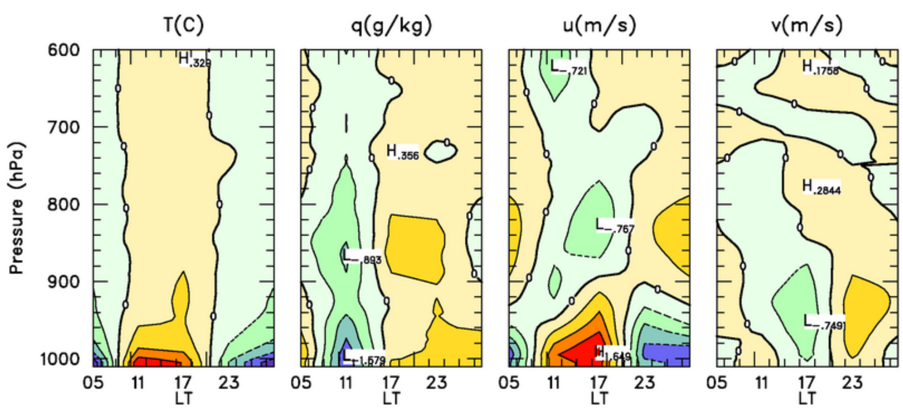
Mitigation of Sri Lanka Island effects on Colombo soundings (Ciesielski et al. 2014)



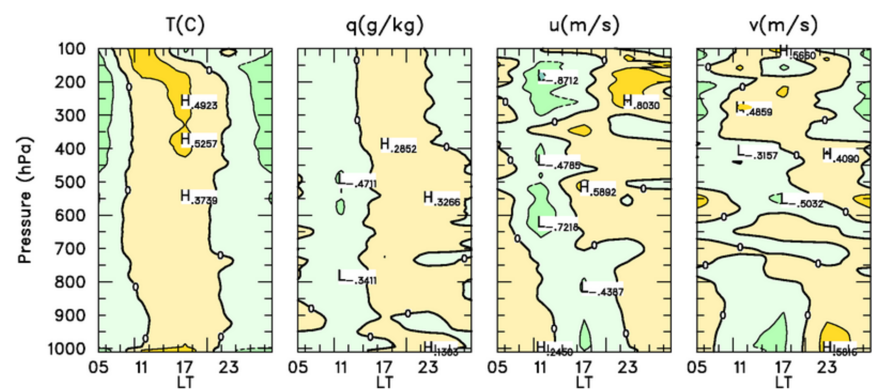
- Peak elevation east of Colombo was ~2500 m



- MQD weighting function showing how the influence of the Colombo data spreads horizontally

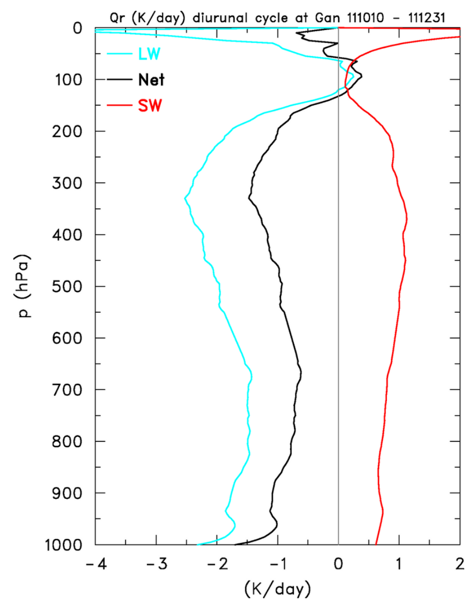


Diurnal cycle anomaly of original Colombo sounding fields.



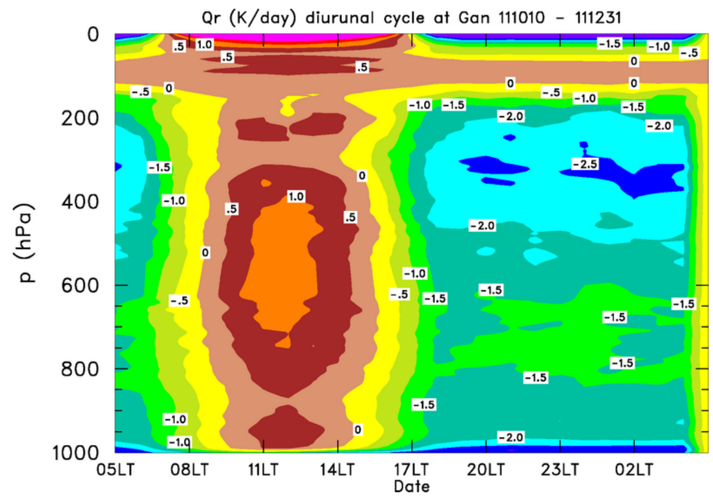
Diurnal cycle anomaly of adjusted Colombo sounding fields; DC at low levels has been effectively muted.

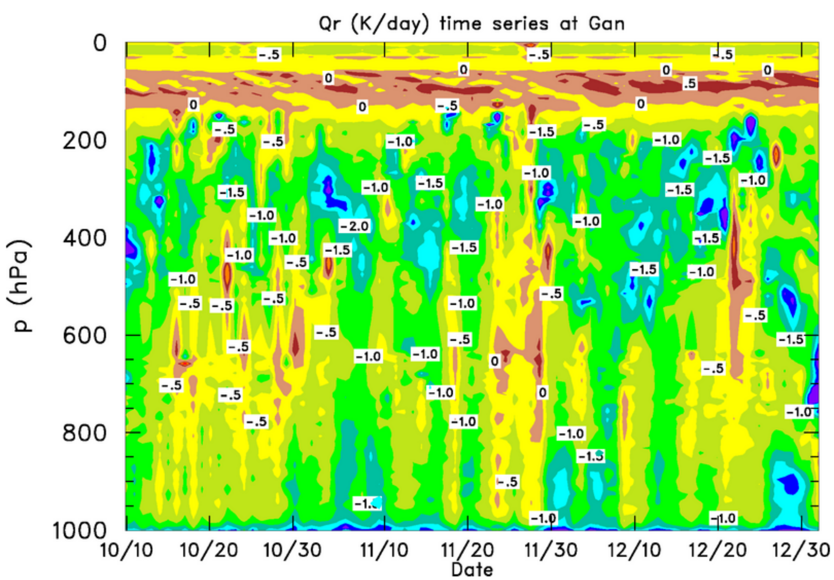
CombRet (Combined Retrival) – radar-lidar cloud retrieval with radiative transfer model (Feng etl al. 2013)



- Period-mean vertical profiles of LW, SW and Q_R (values below melting have been interpolated over)

  - Period mean diurnal cycle of Q_R





- Height-time plot of Q_R at Gan

- To fill in 1 – 9 Oct. period, we used the mean diurnal cycle for the period 12-17 Nov. which had similar rainfall and budget profiles to early October period.

CERES (Clouds and the Earth's Radiant Energy System)

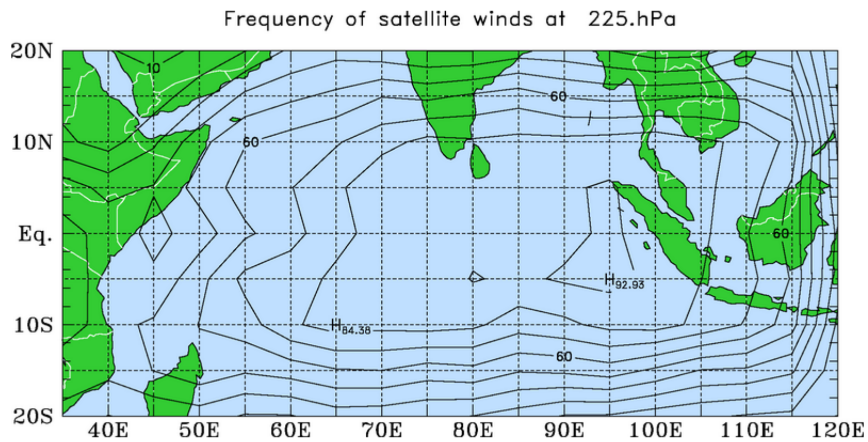
- SYN1deg 3-hr Ed3A Product (Wielicki et al. 1996)

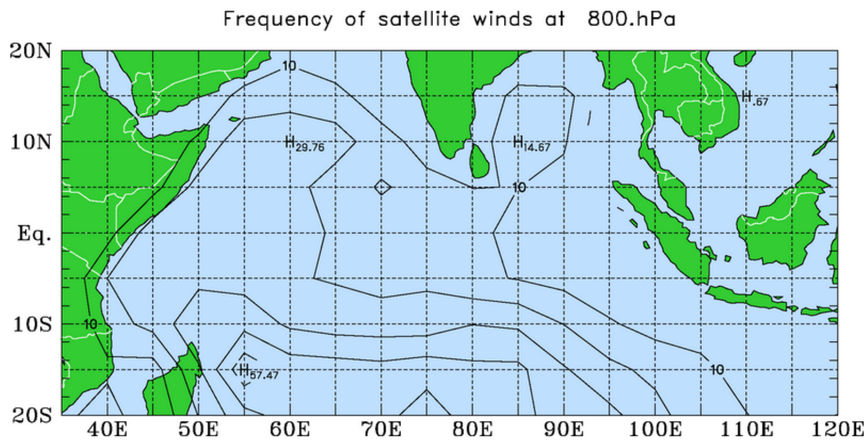
Input: Terra, Aqua, MODIS and GEO (MET-7 at 63E)

Products: TOA and surface radiative fluxes at 1°, 3-hr resolution

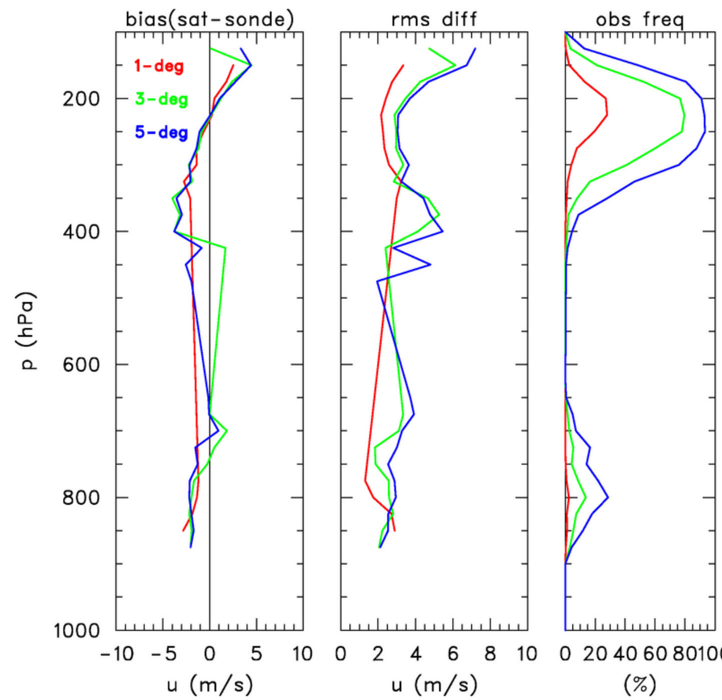
Fluxes are produced using Langley Fu-Liou radiative transfer model

Coverage of CIMSS satellite winds

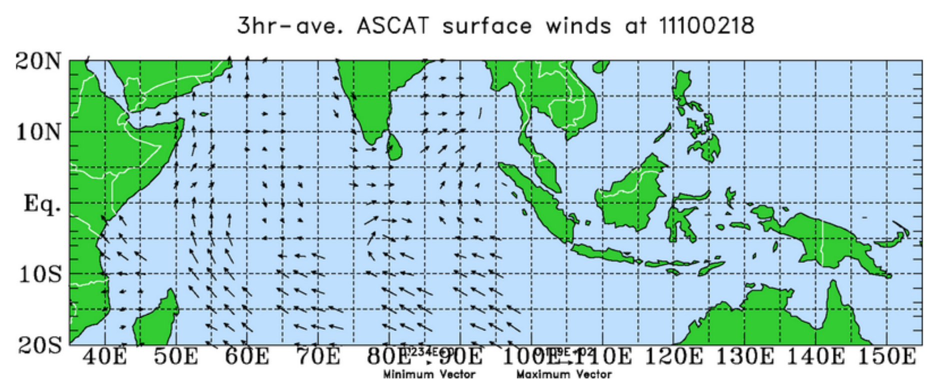




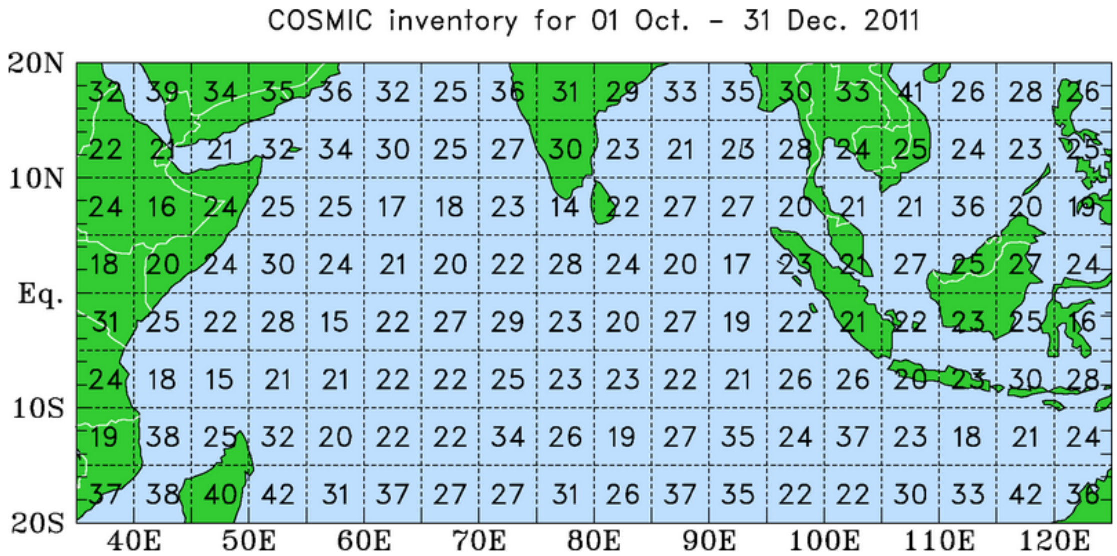
Over central IO CMISS winds are available about ~80% of time at upper level and 20% at 800 hPa (assuming 3-h, 5° resolution and ≥ 3 obs in average)



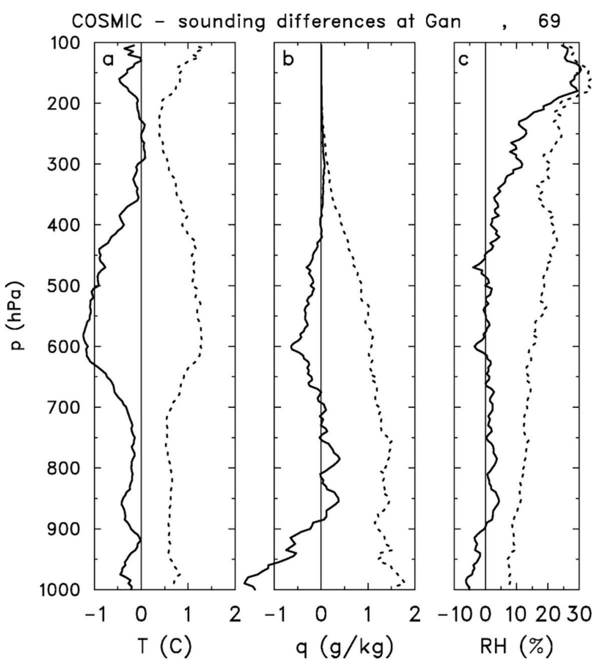
Example of data coverage of ASCAT surface winds for 3 hour window.
At a given point ASCAT winds are available ~15% of the time assuming at 3-h resolution.



COSMIC data



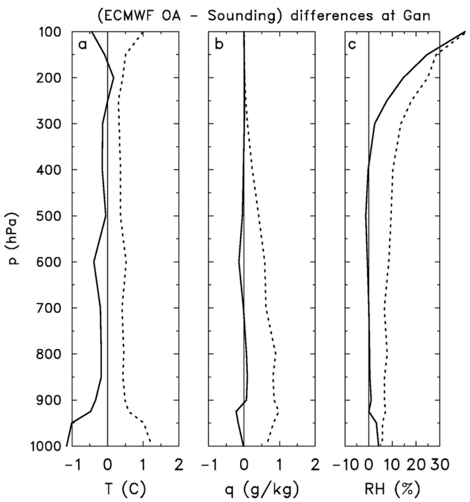
- Number of COSMIC soundings in a 5°×5° box for 3 month period
- Averages ~ 1 sounding every 3-4 days

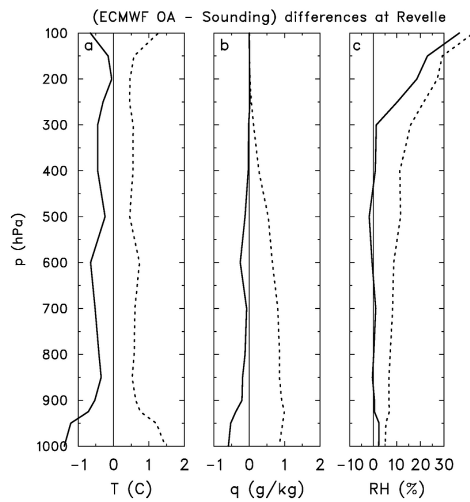


- Biases and RMS differences at Gan between COSMIC data and Gan soundings using COSMIC profiles within 5° radius of Gan
- COSMIC moisture retrievals not used below 850 hPa (issues with penetration of signal under moist conditions.)
- COSMIC shows 1°C cool bias at near 0°C level
- COSMIC upper-level RH bias due to ECMWF moisture bias at these levels.

ECMWF Operational Analyses

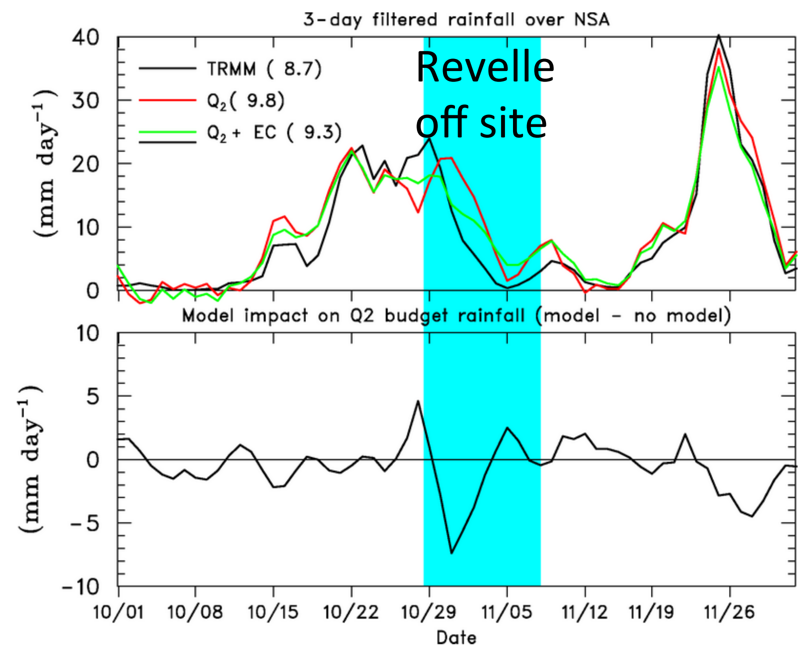
- 6h, 0.25° resolution, 20 pressure levels (sfc to 20 hPa)
- 95% of soundings from core array reached operational centers





- ECMWF model biases and RMS differences from collated soundings
- Model has cool, dry bias at low-levels and moist bias above 250 hPa.

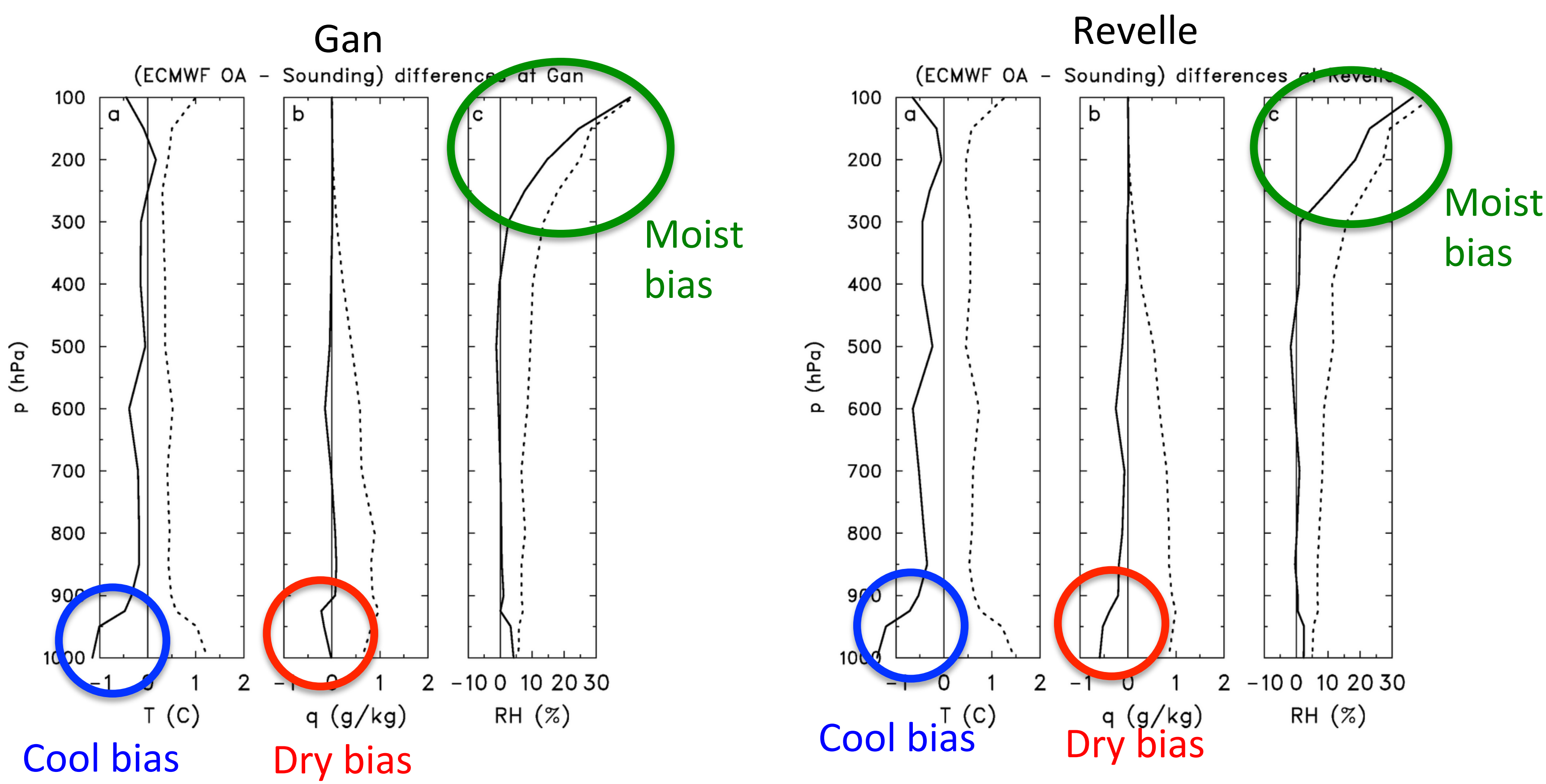
- Using model data to supplement observations has largest impact when ships were off site.



ECMWF Operational Analyses

- 6h, 0.25° resolution, 20 pressure levels (sfc to 20 hPa)
- 95% of soundings from core array reached operational centers
- Comparison of model and sonde data show the model analyses have a slight low-level cool and dry bias and an upper-level moist bias (too much cirrus)
- The main impact of using ECMWF analyses is seen during periods when ships were offsite

Bias (solid curve), RMS difference (dashed)



Heat and Moisture Budgets

Apparent heat source/moisture sink:

(Yanai et al. 1973)

$$Q_1 \equiv c_p[(\partial \bar{T}/\partial t + \bar{\mathbf{v}} \cdot \nabla \bar{T} + (p/p_0)^\kappa \bar{\omega} \partial \bar{\theta}/\partial p)]$$

$$Q_2 \equiv -L(\partial \bar{q}/\partial t + \bar{\mathbf{v}} \cdot \nabla \bar{q} + \bar{\omega} \partial \bar{q}/\partial p)$$

Integrated budgets:

[Definition: $< \ \ > \ \equiv \ 1/g \int_{p_T}^{p_s} (\ ) \, dp$]

$$\text{Heat}: \quad < Q_1 > \ = \ < Q_R > + LP + S \qquad (1)$$

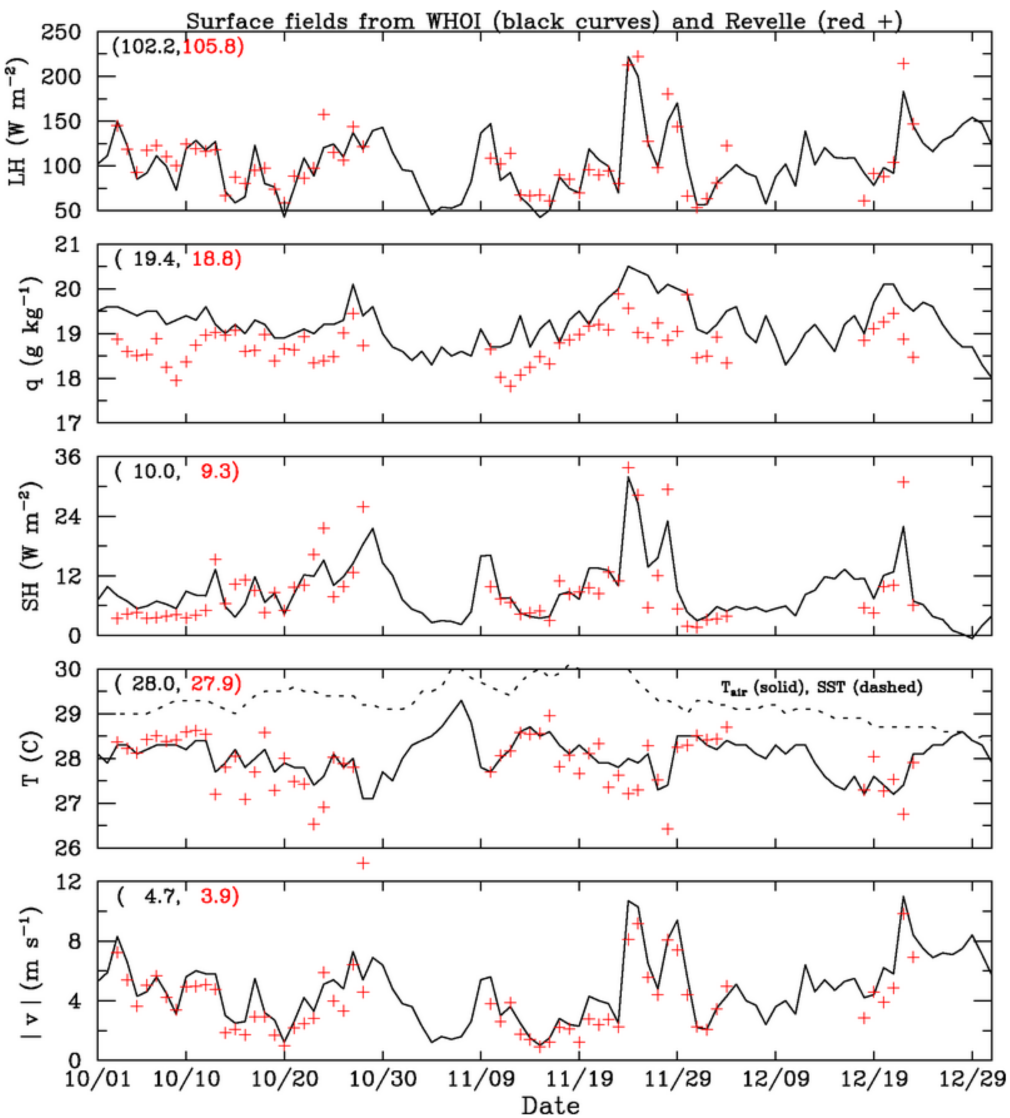
$$\text{Moisture}: \quad < Q_2 > \ = \ L(P - E) \qquad (2)$$

(1) $-$ (2) yields

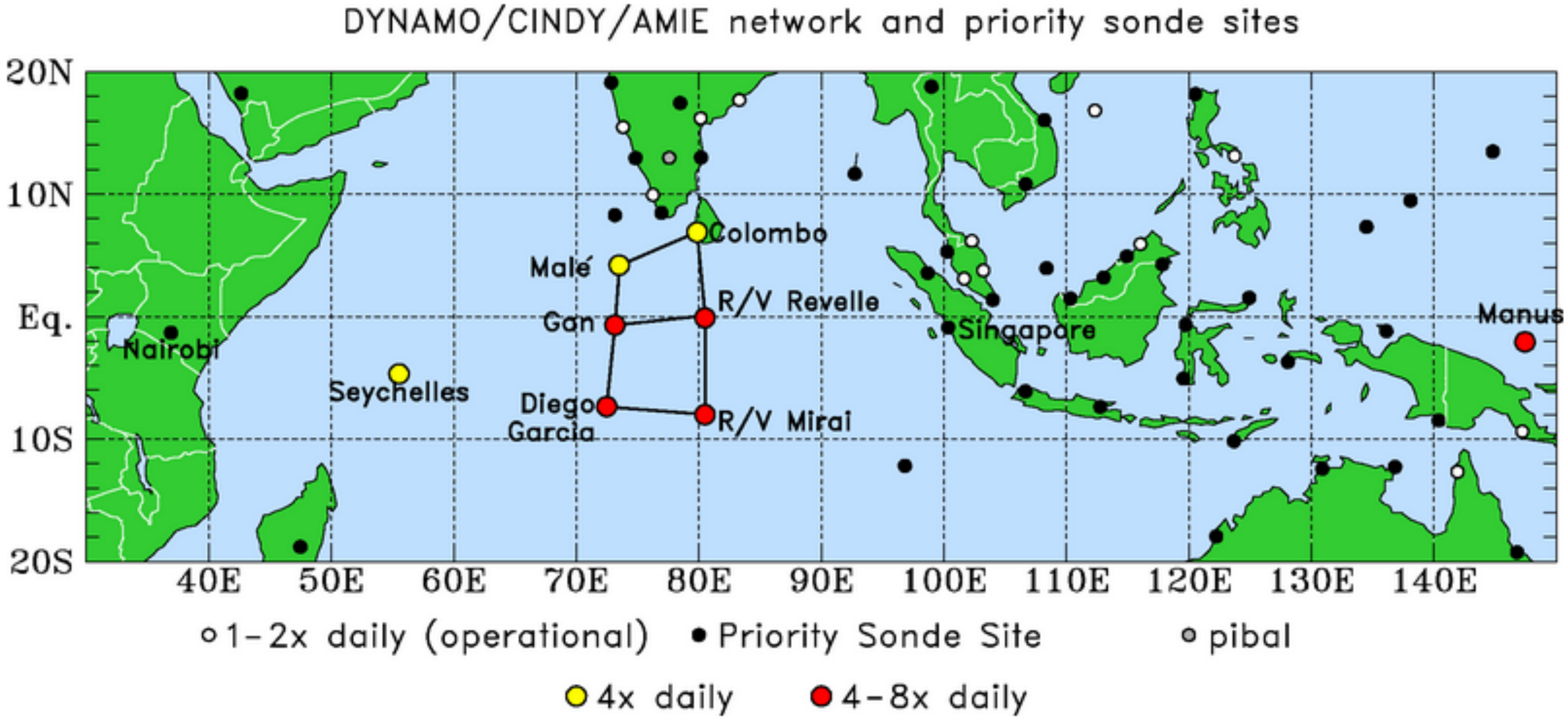
$$< Q_1 > - < Q_2 > \ = \ < Q_R > + S + LE \ , \qquad (3)$$

where P = Precipitation rate, E = Evaporation rate, S = Sensible heat flux

Comparison of fluxes at Revelle (in situ vs WHOI estimated)



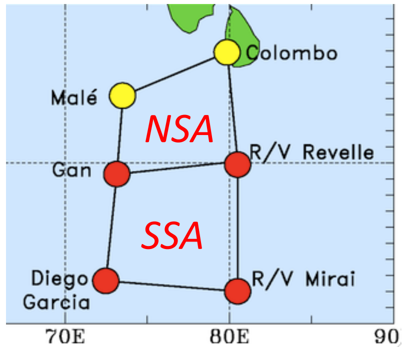
- Period mean LH flux at Revelle LH fluxes is a few percent higher than WHOI
- Surface q from Revelle slightly lower than WHOI values
- Period mean SH flux from Revelle ~5% less than WHOI flux.



DYNAMO/AMIE/CINDY sounding dataset

- Consist of ~26,000 upper-air soundings; ~ half are high-vertical resolution (hi-res)
- All hi-res soundings were corrected, if necessary (Ciesielski et al. 2014)
- Comparisons with independent datasets (such as ground based GPS and MWR retrievals of PW) suggest that the sounding-based humidity observations are of very high quality.
- This study uses the Level 4 (uniform 5-hPa resolution with QC flags) soundings and will focus on the Special Observing Period (**SOP**) 1 Oct. – 30 Nov. 2011.

Enhancements to sounding dataset



1. To better resolve the diurnal cycle and take advantage of the 8/day sampling at sites in the southern array, the 4/day soundings at Malé and Colombo were interpolated to a 3-h time resolution.

2. An adjustment procedure was developed, making use of low-level ECMWF OA, to mitigate the Sri-Lanka island effects (i.e., both flow blocking and the island-induced diurnal cycle) on Colombo soundings (Ciesielski et al. 2014).

- Adjusted Colombo soundings are more representative of open-ocean conditions.

Examples of flow blocking at Colombo (red dot) due to topography to the east of site.